NASA CR-54320

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TOPICAL REPORT **VOLUME 5** APPENDIX

BRUSHLESS ROTATING ELECTRICAL GENERATORS FOR SPACE AUXILIARY POWER SYSTEMS

by

J. N. Ellis and F. A. Collins

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NO. NAS 3-2783

LEAR SIEGLER, INC.

POWER EQUIPMENT DIVISION

CLEVELAND 1, OHIO

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April 26, 1965

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Howard A. Shumaker
NASA Lewis Research Center
Space Power System Division
Solar and Chemical Power Branch

LEAR SIEGLER, INC.
Power Equipment Division
Cleveland, Ohio

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TWO-COIL AND ONE-COIL, OUTSIDE-COIL, LUNDELL, A-C GENERATOR COMPUTER PROGRAM AND TEST DATA

5-7-65

MODEL Brushless TWO OR SINGLE COIL OUTSIDE COIL LUNDELL EWO ______ DESIGN NO(1) M-1

Section	No.	Symbol	Item	Value	Value	Item	No.	Symbol	Section
PARAMETERS	(2)	KVA	GENERATOR KVA	1.04	0	FUND/MAX OF FLD FLUX	(71)	C_1	CONSTANTS
	(3)	E	LINE VOLTS	15	0	WINDING CONSTANT	(72)	C_w	
	(4)	E_{ph}	PHASE VOLTS	8.7	0	POLE CONSTANT	(73)	C_p	
	(5)	m	PHASES	3	0	END EXTENSION ONE TURN	(48)	L_E	
	(5a)	f	FREQUENCY	200	0	DEMAGNETIZATION FACTOR	(74)	C_m	
	(6)	p	POLES	12	0	CROSS MAGNETIZING FACTOR	(75)	C_q	
	(7)	RPM	RPM	2000	.64	POLE EMBRACE	(77)	α	POLE
	(8)	I_{ph}	PHASE CURRENT	40	.45	WIDTH OF POLE(NARROW END)	(76)	b_{p1}	
	(9)	PF	POWER FACTOR	.95	1.15	WIDTH OF POLE(WIDTH END)	(76)	b_{p2}	
	(9a)	K_c	ADJ. FACTOR	1.0	.2	POLE THICKNESS (NARROW END)	(76)	t_{p1}	
	(10)		OPTIONAL LOAD POINT	1.25	.4	POLE THICKNESS (WIDE END)	(76)	t_{p2}	
STATOR STACK	(11)	d	STATOR I.D.	4.80	1.15	POLE LENGTH	(76)	ℓ_p	
	(12)	D	STATOR O.D.	6.63	4.76	ROTOR DIAMETER	(11a)	d_r	
	(13)		GROSS CORE LENGTH	1.0	0	WEIGHT OF ROTOR IRON	(157)	(–)	
	(14)	n_v	NO. OF DUCTS	0	7	POLE FACE LOSS FACTOR	(187)	(K_1)	
	(15)	b_v	WIDTH OF DUCT	0	0	PERM OF LEAKAGE PATH 1	(80)	P_1	PERMEANCE
	(16)	K_i	STACKING FACTOR STATOR	.93	0	PERM OF LEAKAGE PATH 2	(81)	P_2	
	(19)	k	WATTS/LB.	5.0	0	PERM OF LEAKAGE PATH 3	(82)	P_3	
	(20)	B	DENSITY	77.4	0	PERM OF LEAKAGE PATH 4	(83)	P_4	
STATOR SLOT	(21)		TYPE OF SLOT	3	12.4	PERM OF LEAKAGE PATH 5	(84)	P_5	
	(22)	b_o	SLOT OPENING	.120	18.3	PERM OF LEAKAGE PATH 7	(86)	P_7	
	(22)	b_1	SLOT WIDTH TOP	.160	22.2	PERM OF LEAKAGE PATH	(86a)	P_8	
	(22)	b_2		.160	2.8	DIA. OF END BELL AT SMALLEST SECT	(78)	d_{y2}	
	(22)	b_3		.250	.35	THICKNESS OF END BELL " "	(78)	t_{y2}	
	(22)	b_s	SLOT WIDTH	.205	.150	THICKNESS OF HOUSING SECTION	(78)	t_y	
	(22)	h_o		.020	1.7	LENGTH OF HOUSING SECTION	(78)	ℓ_y	
	(22)	h_1		.500	1.0	LENGTH OF PERM PATH 1	(80a)	ℓ_1	
	(22)	h_2		0	2	NO. OF FIELD COILS	(146b)	N_{co}	FIELD
	(22)	h_3		0	350	NO. OF FIELD TURNS/COIL	(146)	NF	
	(22)	h_s	SLOT DEPTH	.550	12	MEAN LENGTH OF FLD. TURN	(147)	ℓ_{tF}	
	(22)	h_t		.030	.0403	FLD. COND. DIA. OR WIDTH	(148)		
	(22)	h_w		.001	0	FLD. COND. THICKNESS	(149)		
	(23)	Q	NO. OF SLOTS	36	100	FLD. TEMP IN °C	(150)	X_f °C	
STATOR WINDING	(28)		TYPE OF WDG.	1	.694	RESISTIVITY OF FLD. COND. @ 20°	(151)	ρ_f	
	(29)		TYPE OF COIL	0	1	NO LOAD SAT.	(87)		
	(30)	n_s	CONDUCTORS/SLOT	14	0	FRICTION & WINDAGE	(183)	(F&W)	
	(31)	y	SLOTS SPANNED	3	38.3	SPECIAL PERMEANCE	64a	λ	
	(32)	c	PARALLEL CIRCUITS	2	11E	STATOR LAM MATERIAL M22	(18)		MAT'L
	(33)		STRAND DIA. OR WIDTH	.0508	12	POLE MATERIAL 1010	(18)		
	(34)	N_{st}	STRANDS/CONDUCTOR IN DEPTH	1	12	YOKE MATERIAL 1010	(18)		
	(34a)	N'_{st}	STRANDS/CONDUCTOR	2					
	(39)		STATOR STRAND T'KNS.	0					
	(35)	d_b	DIA. OF PIN	.25					
	(36)	ℓ_{e2}	COIL EXT. STR. PORT	.2					
	(37)	h_{st}	UNINS. STRD. HT.	.0508					
	(38)	h'_{st}	DIST. BTWN. C_L OF STD.	.053					
	(42a)		PHASE BELT ANGLE	60					
	(40)	γ_{sk}	STATOR SLOT SKEW	0					
	(50)	X°C	STATOR TEMP °C	100					
	(51)	ρ_s	RES'TVY STA. COND. @ 20 °C	.694					
GAP	(78)	ℓ_{g2}	LENGTH OF GAP (g2)	1.20					
	(78)	d_{g2}	DIAMETER AT GAP (g2)	2.0					
	(59)	g	MAIN AIR GAP	.018					
	(59a)	g2	AUXILIARY AIR GAP	.020					

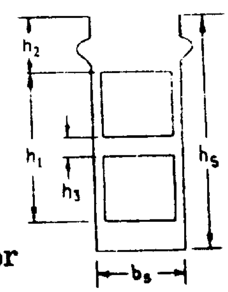
STATOR SLOT	POLE
DAMPER SLOT	REMARKS

DESIGNER ______ DATE ______

MA-1

REV. A

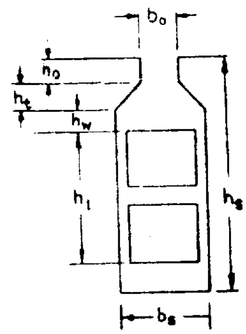
(a) Open Slots



TYPE 1

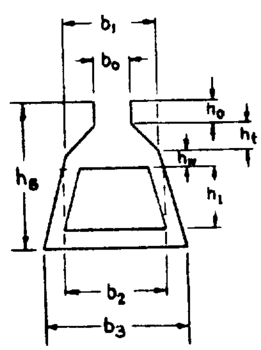
(Type 5 is an open slot with 1 conductor per slot)

(b) Constant Slot Width



TYPE 2

(c) Constant Tooth Width

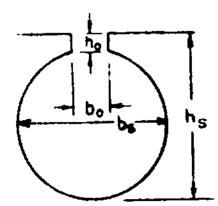


TYPE 3

b_s for type 3 is

$$b_s = \left(\frac{b_1 + b_3}{2}\right)$$

(d) Round Slots



TYPE 4

TWO OR SINGLE COIL OUTSIDE COIL LUNDELL

SUMMARY OF DESIGN CALCULATIONS – – – – – – – – (OUTPUT) 40 AMPS 5/7/65

MODEL NO. ______ EWO ______ DESIGN NO ______

Section	No.	Symbol	Item	Value	Value	Item	No.	Symbol	Section
STATOR	(17)	(ℓ_s)	SOLID CORE LENGTH	.93000	1.25556	CARTER COEFFICIENT	(67)	(K_s)	
STATOR	(24)	(h_c)	DEPTH BELOW SLOT	.36500	.02256	EFFECTIVE AIR GAP	(69)	(g_e)	
STATOR	(26)	(τ_s)	SLOT PITCH	.41893	1.00935	FUND/MAX OF FLD. FLUX	(71)	(C_1)	CONSTANTS
STATOR	(27)	(τ_s1/3)	SLOT PITCH 1/3 DIST. UP	.45095	.45450	WINDING CONST.	(72)	(C_w)	CONSTANTS
STATOR	(42)	(K_{sk})	SKEW FACTOR	1.00000	.65952	POLE CONST.	(73)	(C_p)	CONSTANTS
STATOR	(43)	(K_d)	DIST. FACTOR	1.00000	2.86137	END. EXT. ONE TURN	(48)	(L_E)	CONSTANTS
STATOR	(44)	(K_p)	PITCH FACTOR	.99999	.86321	DEMAGNETIZING FACTOR	(74)	(C_M)	CONSTANTS
STATOR	(45)	(n_e)	EFF. CONDUCTORS	251.99999	.40680	CROSS MAGNETIZING FACTOR	(75)	(C_q)	CONSTANTS
STATOR	(46)	(a_c)	COND. AREA	.00405	668.36000	AMP COND/IN	(128)	(A)	
STATOR	(47)	(S_s)	CURRENT DENSITY (STA.)	4936.30000	1.62137	REACTANCE FACTOR	(129)	(X)	
STATOR	(49)	(ℓ_t)	1/2 MEAN TURN LENGTH	3.68130	103.18640	LEAKAGE REACTANCE	(130)	(X_ℓ)	
STATOR	(53)	(R_{ph})	COLD STA. RES. @ 20° C	.02792	98.05278	REACTANCE DIRECT AXIS	(131)	(X_{ad})	
STATOR	(54)	(R_{ph})	HOT STA. RES. @ X° C	.03680	43.21403	REACTANCE QUAD. AXIS	(132)	(X_{aq})	
STATOR	(55)	(EF_{top})	EDDY FACTOR TOP	1.01840	201.23918	SYN REACT DIRECT AXIS	(133)	(X_d)	REACTANCE
STATOR	(56)	(EF_{bot})	EDDY FACTOR BOT	1.00260	146.40043	SYN REACT QUAD AXIS	(134)	(X_q)	REACTANCE
STATOR	(62)	(λ_i)	STATOR COND. PERM.	16.12100	57.75085	FIELD LEAKAGE REACT	(160)	(X_f)	REACTANCE
STATOR	(63)	(λ_e)	END PERM.	9.22020	.21372	FIELD SELF INDUCTANCE	(161)	(L_f)	REACTANCE
STATOR	(65)	( )	WT. OF STA COPPER	2.54410	160.93725	UNSAT. TRANS. REACT	(166)	(X'_{du})	REACTANCE
STATOR	(66)	( )	WT. OF STA IRON	3.27120	141.62478	SAT. TRANS. REACT	(167)	(X'_d)	REACTANCE
	(41)	(τ_p)	POLE PITCH	1.25660	141.62478	SUB. TRANS REACT DIRECT AX.	(168)	(X''_d)	REACTANCE
	(157)	(–)	WT. OF ROTOR IRON	.00000	146.40043	SUB. TRANS REACT QUAD AX.	(169)	(X''_q)	REACTANCE
	(145)	(V_r)	PERIPHERAL SPEED	2492.33600	144.01261	NEG SEQUENCE REACT	(170)	(X_2)	REACTANCE
FIELD	(153)	(a_{cf})	FLD COND. AREA	.00127	38.76238	ZERO SEQUENCE REACT	(172)	(X_o)	REACTANCE
FIELD	(154)	(R_f)	COLD FLD RES @ 20° C	2.28620	.04674	OPEN CIR. TIME CONST.	(176)	(T'_{do})	TIME CONST.
FIELD	(155)	(R_f)	HOT FLD RES @ X° C	3.01310	.00869	ARM TIME CONST.	(177)	(T_a)	TIME CONST.
FIELD	(156)	(–)	WT OF FLD COPPER	1.71880	.03289	TRANS TIME CONST.	(178)	(T'_d)	TIME CONST.
PERMEANCE	(80)	(P_1)	PERM OF LEAKAGE PATH 1	.28710	.01000	SUB. TRANS TIME CONST.	(179)	(T''_d)	TIME CONST.
PERMEANCE	(81)	(P_2)	PERM OF LEAKAGE PATH 2	2.41030	410.99000	TOTAL FLUX	(88)	(ϕ_T)	MAGNETIZATION
PERMEANCE	(82)	(P_3)	PERM OF LEAKAGE PATH 3	.50657	22.58800	FLUX PER POLE	(92)	(ϕ_p)	MAGNETIZATION
PERMEANCE	(83)	(P_4)	PERM OF LEAKAGE PATH 4	1.18210	27.25500	GAP DENSITY (MAIN)	(95)	(B_g)	MAGNETIZATION
PERMEANCE	(84)	(P_5)	PERM OF LEAKAGE PATH 5	12.40000	46.34600	TOOTH DENSITY	(91)	(B_t)	MAGNETIZATION
PERMEANCE	(86)	(P_7)	PERM OF LEAKAGE PATH 7	18.30000	33.27200	CORE DENSITY	(94)	(B_c)	MAGNETIZATION
PERMEANCE	(86a)	(P_8)	PERM OF LEAKAGE PATH 8	22.20000	1.37760	TOOTH AMPERE TURNS	(97)	(F_t)	MAGNETIZATION
	(180)	(FSC)	SHORT CIR NI	1339.28700	.66393	CORE AMPERE TURNS	(98)	(F_c)	MAGNETIZATION
	(181)	(SCR)	SHORT CIR. RATIO	.53400	192.78000	GAP AMPERE TURNS (MAIN)	(96)	(F_g)	MAGNETIZATION

PERCENT LOAD			0			100	150	200	OPTIONAL
(ϕ_ℓ)	(100a)	LEAKAGE FLUX	20.473	(ϕ_ℓ)	(197a)	50.953	.000	.000	.000
(ϕ_{pt})	(102a)	TOTAL FLUX POLE	26.000	(ϕ_{ptl})	(213a)	46.749	.000	.000	.000
(B_p)	(103a)	POLE DENSITY	56.522	(B_{pl})	(213b)	101.620	.000	.000	.000
(B_{g2})	(122)	AUX. GAP DENSITY	22.327	(B_{g2L})	(224)	41.229	.000	.000	.000
(B_{y2})	(125)	END BELL DENSITY	56.105	(B_{y2L})	(228)	104.410	.000	.000	.000
(B_y)	(126a)	HOUSING DENSITY	52.690	(B_{yl})	(229b)	97.296	.000	.000	.000
(F_{nl})	(127)	TOTAL NI/COIL	715.190	(F_{fl})	(236)	1967.300	.000	.000	.000
(I_{fnl})	(127a)	FIELD AMP./COIL	1.021	(I_{ffl})	(237)	2.810	.000	.000	.000
(S_f)	(127c)	CUR. DENSITY FIELD	801.400	(S_{fl})	(239)	2204.400	.000	.000	.000
(E_{fnl})	(127b)	FIELD VOLTS/COIL	4.671	(E_{ffl})	(238)	16.936	.000	.000	.000
(W_c)	(185)	STA CORE LOSS	2.790	(W_c)	(185)	2.790	2.790	2.790	2.790
(W_{tnl})	(184)	STA TOOTH LOSS	3.961	(W_{tfl})	(242)	6.299	.000	.000	.000
($I^2 R_s$)	(194)	STATOR CU LOSS	.000	($I^2 R_l$)	(245)	176.640	.000	.000	.000
(–)	(195)	EDDY LOSS	.000	(–)	(246)	1.854	.000	.000	.000
(W_{pnl})	(186)	POLE FACE LOSS	25.608	(W_{pfl})	(243)	74.630	.000	.000	.000
($I^2 R_f$)	(182)	FIELD COIL LOSS	2.386	($I^2 R_{fl}$)	(241)	47.597	.000	.000	.000
(F&W)	(183)	F&W LOSS	12.813	(F&W)	(183)	12.813	12.813	12.813	12.813
(–)	(196)	TOTAL LOSSES	47.558	(–)	(247)	322.625	.000	.000	.000
(–)	(–)	PERCENT EFF.	.000	(–)	(251)	75.455	.000	.000	.000

DESIGNER ______________ DATE ______________

REV. A

TWO OR SINGLE COIL OUTSIDE COIL LUNDELL

NO LOAD SATURATION OUTPUT SHEET

ITEMS → / ↓ % VOLTS	(3) (E) VOLTS (100a) ϕ_ℓ LEAKAGE FLUX	(91) B_t STA. TOOTH DENSITY (102a) ϕPT TOTAL FLUX/POLE	(97) F_t STA. TOOTH NI (103a) B_p POLE DENSITY	(94) B_c STA. CORE DENSITY (125) B_{y2} END BELL DENSITY	(98) F_c STA. CORE NI (126a) B_y HOUSING DENSITY	(96) F_g MAIN GAP DENSITY (127) F_{nl} TOTAL NI
80%	12.00000 16.36852	37.07680 20.79848	1.00413 45.21410	26.61760 44.88040	.53820 42.14798	154.2240 572.7451[illegible]
90%	13.50000 18.41840	41.71140 23.39893	1.16975 50.86724	29.94480 50.49077	.59777 47.41781	173.5020 643.70284
100%	15.00000 20.47308	46.34600 26.00018	1.37763 56.52213	33.27200 56.10502	.66393 52.69050	192.78000 715.19500
110%	16.50000 22.53202	50.98060 28.60213	1.62244 62.17856	36.59920 61.72390	.73741 57.96635	212.05800 787.5196[illegible]
120%	18.00000 24.59598	55.61520 31.20493	1.91075 67.83680	39.92640 67.34973	.81903 63.24634	231.33600 861.4856
130%	19.50000 26.66640	60.24980 33.80880	2.25030 73.49739	43.25360 72.98541	.92087 68.53237	250.614[illegible] 937.683[illegible]
140%	21.00000 28.74384	64.88440 36.41384	2.65020 79.16052	46.58080 78.63329	1.03561 73.82494	269.892[illegible] 1017.1682[illegible]
150%	22.50000 30.84343	69.51900 39.02257	3.25327 84.83167	49.90800 84.30538	1.16465 79.13381	289.170[illegible] 1101.20370
160%	24.00000 32.96386	74.15360 41.63477	4.04631 90.51038	53.23520 90.03001	1.30976 84.47359	308.448[illegible] 1198.95540

REV. A

INPUT PARAMETERS

1.04	15.	8.7	3.	200.	12.	2000.	50.	.95	1.
1.25	4.8	6.63	1.	0.	0.	.93	5.	77.4	3.
.12	.16	.16	.25	.205	.02	.5	0.	0.	.55
.03	.001	36.	1.	0.	14.	3.	2.	.0508	1.
2.	0.	.25	.2	.0508	.053	60.	0.	100.	.694
1.2	2.	.018	.02	0.	0.	0.	0.	0.	0.
.64	.45	1.15	.2	.4	1.15	4.76	0.	7.	0.
0.	0.	0.	12.4	18.3	22.2	2.8	.35	.15	1.7
1.	2.	350.	12.	.0403	0.	100.	.694	1.	0.
38.3									

SATURATION CURVE VALUES FOR STATOR

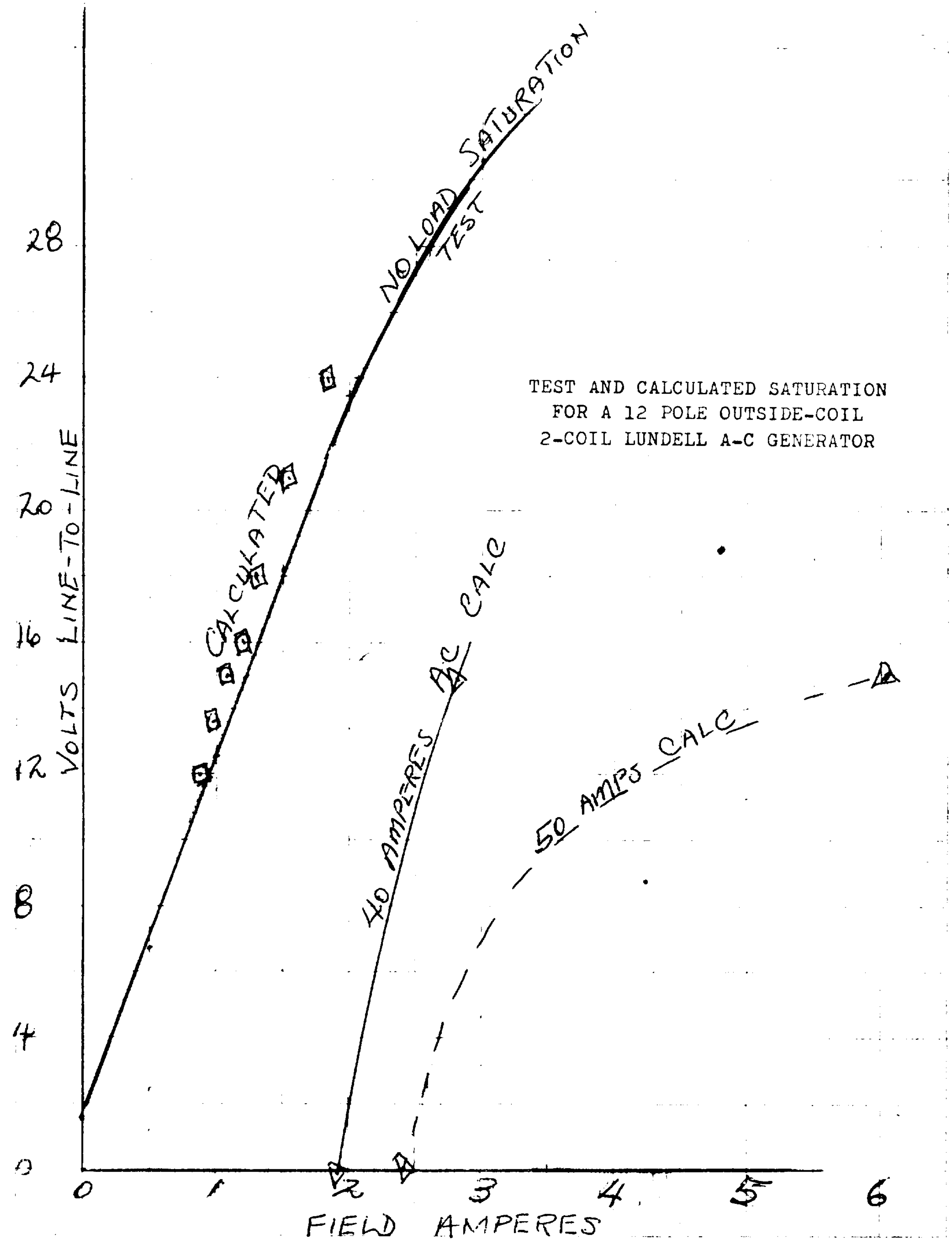
132.	18.	1.	40.	2.	66.
5.	76.	8.	85.	14.5	102.
101.	114.	300.	132.	1000.	

SATURATION CURVE VALUES FOR POLE

140.	0.	1.6	10.	2.3	20.
3.3	30.	4.2	60.	7.3	70.
9.2	80.	12.5	85.	15.	90.
20.	100.	40.	108.	100.	112.
160.	126.	500.	140.	1000.	

SATURATION CURVE VALUES FOR YOKE

140.	0.	1.6	10.	2.3	20.
3.3	30.	4.2	60.	7.3	70.
9.2	80.	12.5	85.	15.	90.
20.	100.	40.	108.	100.	112.
160.	126.	500.	140.	1000.	


NO LOAD SATURATION
TEST
CALCULATED
40 AMPERES AC CALC
50 AMPS CALC
TEST AND CALCULATED SATURATION
FOR A 12 POLE OUTSIDE-COIL
2-COIL LUNDELL A-C GENERATOR
VOLTS LINE-TO-LINE
FIELD AMPERES
0
4
8
12
16
20
24
28
1
2
3
4
5
6

COMPUTER PROCEDURE FOR

SINGLE OR 2 COIL

OUTSIDE COIL LUNDELL DESIGN CALCULATIONS

1. Clear core (no switch control).
2. Insert output Form #1 into typewriter, set margin for correct output.
3. Load pass #1 followed by input #1 (output printed plus punched cards).
4. Reset and load pass #2 followed by output from pass #1 (output punched cards).
5. Reset and load pass #3 followed by output from pass #2 (output punched cards).
6. Reset and load pass #4 followed by output from pass #3(output punched cards).
7. Reset and load pass #5 followed by saturation curve values* and output from pass #4 (output punched cards).
8. Reset and load pass #6 followed by output from pass #5 (output printed plus punch cards).
9. Reset and load pass #7 followed by output from pass #6 (output punched cards).
10. Reset and load pass #8 followed by saturation curve values* and output from pass #7 (output punched cards).
11. Reset and load pass #9 followed by output from pass #8 (output printed plus punched cards if no load saturation curve required).
12. If there is punch card output from pass #9 a no load saturation curve is required. Insert output Form #2 into typewriter and reset margin. Load pass #10 followed by saturation curve values and output from pass #9 (output printed).

* Saturation curves are loaded in order shown on Input Form #1.

ALL INPUT PARAMETERS ARE IN FORMAT F7.0 (FIG. 1)

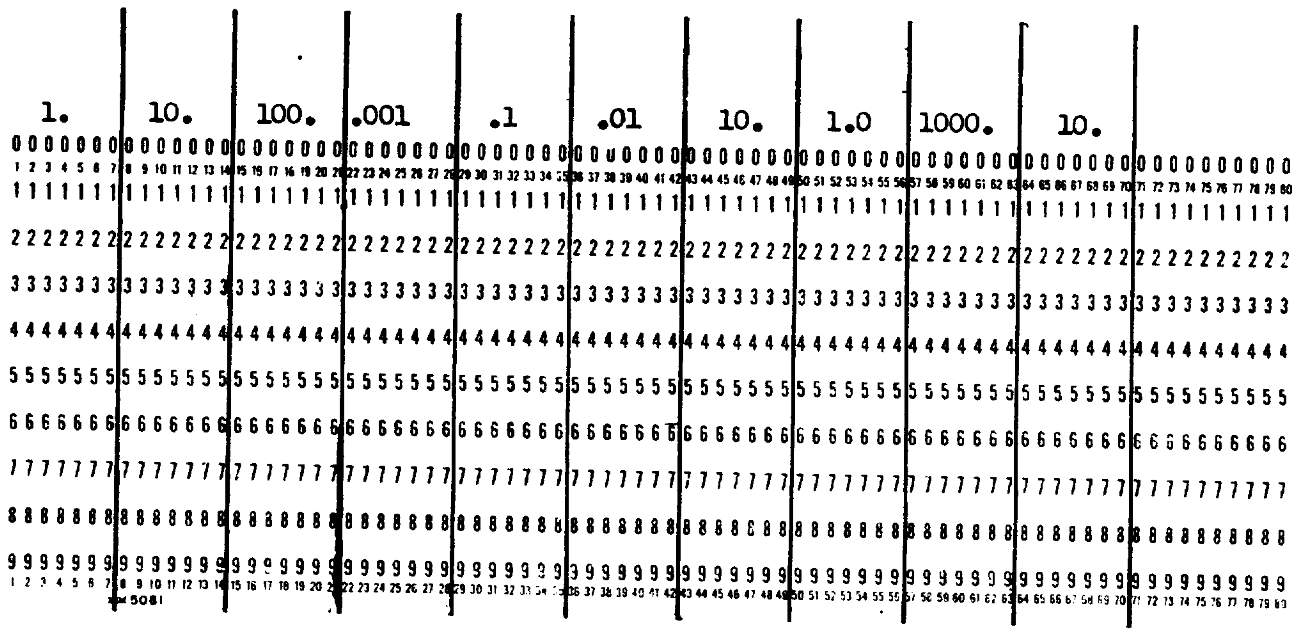


FIG. 1

ALL SATURATION CURVE VALUES ARE IN FORMAT F10.0 (FIG. 2)
(ALL SATURATION CURVES MUST HAVE 5 CARDS)

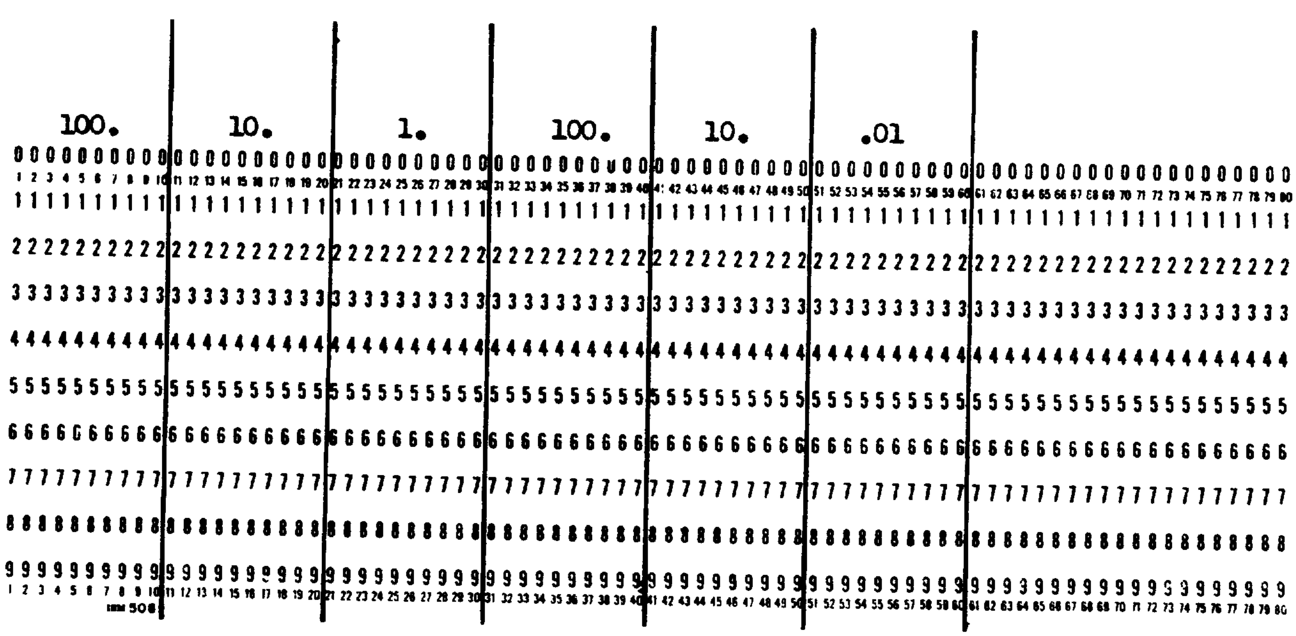


FIG. 2

SINGLE)
OR) OUTSIDE COIL LUNDELL
TWO COIL)

Calculation Number	Electrical Symbol	Fortran Symbol
		A, a
(128)	A	A
(46)	a_c	AC
(153)	a_{cf}	AS
(70)	A_{g2}	A2
(124)	A_{y2}	AY2
(79)	a_p	AP
		B, b
(20)	B	BK
(22)	b_o	BO
(94)	$B_c,$	BC1
(76)	b_{p1}	BP1
(76)	b_{p2}	BP2
(95)	$B_g,$	BG1
(122)	B_{g2}	BG2
(224)	B_{g2FL}	BG2L
(58)	b_t	
(57a)	b_t 1/3	SM
(91)	$B_T,$	BT1
(57)	b_{tm}	TM

Calculation Number	Electrical Symbol	Fortran Symbol
(126a)	B_y	BY
(229b)	B_{yL}	BYL
(228)	B_{y2L}	BY2L
(15)	b_v	BV
(125)	B_{y2}	BY2
	C, c	
(32)	c	C
(71)	C_1	C1
(74)	C_M	CM
(73)	C_P	CP
(75)	C_q	CQ
(72)	C_W	CW
	D, d	
(12)	D	DU
(11)	d	DI
(35)	d_b	DB
(11a)	d_r	DR
(78)	d_{g2}	DG2
(78)	d_{y2}	DY2

Calculation Number	Electrical Symbol	Fortran Symbol
	E, e	
(3)	E	EE
(55)	EF_{TOP}	ET
(56)	EF_{BOT}	EB
(238)	E_{FFL}	EPFL
(127b)	E_{FNL}	EPNL
(4)	E_{PH}	EP
	F, f	
(5a)	f	F
(98)	F_c,	FC
(236)	F_{FL}	FFL
(96)	F_g,	FG
(123)	F_{g2}	FG2
(225)	$F_{g2\,FL}$	FG2 L
(127)	F_{NL}	FNL
(104)	F_P	FP
(126b)	F_y	FY
(180)	F_{SC}	FSC
(97)	F_T,	FT
(183)	F & W	WF
(126)	F_{y2}	FY2

Calculation Number	Electrical Symbol	Fortran Symbol
(229c)	F_{yL}	FYL
(229)	F_{y2L}	FY2L
	G, g	
(59)	g	GC
(59a)	g_2	G2
(69)	g_e	GE
	H, h	
(24)	h_c	HC
(38)	h'_{ST}	SD
(39)	h_{ST}	SH
	I, i	
(237)	I_{FFL}	AIFL
(127a)	I_{FNL}	AINL
(8)	I_{PH}	PI
(182)	I^2R_F	FEL
(241)	I^2R_F	FCUL
(194)	I^2R	PS
(245)	I^2R_L	SCUL

Calculation Number	Electrical Symbol	Fortran Symbol
	K, k	
(19)	k	WL
(9a)	K_c	CK
(43)	K_d	DF
(63)	K_e	EK
(16)	K_i	SF
(44)	K_p	CF
(67)	K_s	CC
(42)	K_{SK}	FS
(2)	K_{VA}	VA
(61)	K_X	FF
	L, l	
(13)	ℓ	CL
(80)	ℓ_1	AL1
(80)	ℓ_2	AL2
(82)	ℓ_3	AL3
(48)	L_E	EL
(36)	ℓ_{e2}	CE
(161)	L_F	SI
(78)	ℓ_{g2}	ALG2

Calculation Number	Electrical Symbol	Fortran Symbol
(76)	ℓ_P	ALP
(17)	ℓ_s	SS
(49)	ℓ_t	HM
(147)	ℓ_{tf}	FE
(78)	ℓ_y	ALY
	M, m	
(5)	m	PN
	N, n	
(146a)	N_{co}	COILS
(146)	N_F	PT
(45)	n_e	EC
(30)	n_s	SC
(34)	N_{ST}	SN
(34a)	N'_{ST}	SN1
(14)	n_v	HV
	P, p	
(6)	p	PX
(9)	PF	PF
(80)	P_1	P1
(81)	P_2	P2
(82)	P_3	P3

Calculation Number	Electrical Symbol	Fortran Symbol
(83)	P_4	P4
(84)	P_5	P5
(86)	P_7	P7
	Q, q	
(23)	Q	QQ
(25)	q	QN
	R, r	
(154)	R_f (cold)	FK
(155)	R_f (hot)	FR
(7)	RPM	RPM
(53)	R_{SPH} (cold)	RG
(54)	R_{RPH} (hot)	RP
	S, s	
(181)	SCR	SCR
(127c)	S_F	CD
(47)	S_S	S
	T, t	
(177)	T_a	TA
(178)	T'_d	T5
(176)	T'_{do}	TC

Calculation Number	Electrical Symbol	Fortran Symbol
(78)	t_y	TY
(78)	t_{y2}	TY2
	V, v	
(145)	V_r	VR
	W, w	
(185)	W_C	WQ
(186)	W_{NPL}	WN
(243)	W_{PFL}	WNL
(242)	W_{TFL}	WTFL
(184)	W_{TNL}	WT
	X, x	
(129)	X	XR
(131)	X_{ad}	XD
(132)	X_{aq}	XQ
(133)	X_d	XA
(167)	X'_d	XS
(168)	X''_d	XX
(166)	X'_{du}	XU
(160)	X'_F	XF

Calculation Number	Electrical Symbol	Fortran Symbol
(150)	X_f °C	T2
(130)	X_ℓ	XL
(169)	X_q''	XY
(134)	X_q	XB
(50)	X_s °C	TI
(170)	X_2	XN
(172)	X_o	XO
	Y, y	
(31)	y	YY
	Ø	
(108)	$Ø_{g2}$	PG2
(221)	$Ø_{g2L}$	PG2L
(100)	$Ø_\ell$	PL
(118)	$Ø_{\ell 5}$	PL5
(99)	$Ø_{\ell 7}$	PL7
(226)	$Ø_{5L}$	PL5L
(207)	$Ø_{7L}$	PL7L
(92)	$Ø_p$	FQ

Calculation Number	Electrical Symbol	Fortran Symbol
(213)	ϕ_{PL}	FQL
(102)	ϕ_{PT}	PLT
(88)	ϕ_T	TG
(227)	ϕ_{y2L}	PG2L
	τ	
(41)	τ_p	TP
(26)	τ_s	TS
(40)	τ_{SK}	SK
(27)	$\tau_{S\,1/3}$	TT
	λ	
(64)	λ_E	EW
(62)	λ_i	PC
(64a)	λ_z	ALZ
	ρ	
(151)	ρ_f	RR
(152)	$\rho_{f\ (hot)}$	
(51)	ρ_s	RS
	α	
(77)	α	PE

```
C     PASS  1  OUTSIDE COIL LUNDELL
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    2 FORMAT(F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0)
    3 FORMAT(9X F12.5,2X F12.5)
    7 READ2,VA,EE,EP,PN,F,PX,RPM,PI,PF,CK
      READ2,POL,DI,DU,CL,HV,BV,SF,WL,BK,ZZ
      READ2,BO,B1,B2,B3,BS,HO,HX,HY,HZ,HS
      READ2,HT,HW,QQ,W,RF,SC,YY,C,DW,SN
      READ2,SN1,DW1,DB,CE,SH,SD,PBA,SK,T1,RS
      READ2,ALG2,DG2,GC,G2,C1,CW,CP,EL,CM,CQ
      READ2,PE,BP1,BP2,TP1,TP2,ALP,DR,WR,D1,P1
      READ2,P2,P3,P4,P5,P7,P8,DY2,TY2,TY,ALY
      READ2,AL1,COILS,PT,FE,RD,RT,T2,RR,SNL,WF
      READ1,ALZ
      SS=SF*(CL-HV*BV)
      HC=(DU-DI-2.0*HS)*0.5
      QN=QQ/(PX*PN)
      TS=3.142*DI/QQ
      IF(ZZ-4.0)9,10,9
    9 TT=(0.667*HS+DI)*3.142/QQ
      GO TO 11
   10 TT=3.1416*(DI+2.*HO+1.32*BS)/QQ
   11 IF(ZZ-1.0)12,12,13
   12 BO=BS
      CC=(5.*GC+BS)*TS/((5.*GC+BS)*TS-BS*BS)
      GO TO 14
   13 QC=(4.44*GC+0.75*BO)*TS
      CC=QC/(QC-BO*BO)
   14 CS=YY/(PN*QN)
```

```
      TP=3.1416*DI/PX
      IF(SK)18,18,19
   18 FS=1.0
      GO TO 20
   19 FS=SIN(1.571*SK/TP)*TP/(1.571*SK)
   20 IF(PBA-60.)21,21,22
   21 D=1.0
      GO TO 95
   22 D=2.0
   95 I=QN
      U=I
      IF(QN-U)23,23,24
   24 U=PX*PN
      XX=U
      N=U
      DO 25 K=1,N
      Z=U/XX
      I=Z
      Z1=I
      IF(Z-Z1)26,26,25
   26 ZY=QQ/XX
      I=ZY
      Z1=I
      IF(ZY-Z1)27,27,25
   25 XX=XX-1.
   23 ZY=QN
   27 DF=SIN(.5236*D)/(ZY*D*SIN(.5236/ZY))
      CF=SIN(YY*1.571/(PN*QN))
      EC=QQ*SC*CF*FS/C
```

```
      GE=CC*GC
      IF(C1)29,28,29
   28 C1=0.649*LOG(PE)+1.359
   29 IF(CW)30,30,31
   30 CW=0.707*EE*C1*DF/(EP*PN)
   31 IF(CP)32,32,33
   32 CP=PE*(LOG(GC/TP)*.0378+1.191)
   33 IF(EL)34,34,42
   34 IF(RF)35,35,41
   35 IF(PX-2.0)36,36,37
   36 U=1.3
      GO TO 40
   37 IF(PX-4.0)38,38,39
   38 U=1.5
      GO TO 40
   39 U=1.7
   40 EL=3.142*U*YY*(DI+HS)/QQ+0.5
      GO TO 42
   41 EL=2.0*CE+3.142*(0.5*HX+DB)+YY*TS*TS/SQRT(TS*TS-BS*BS)
   42 AA=1.571*PE
      AB=3.142*PE
      IF(CM)43,43,44
   43 CM=(AB+SIN(AB))/(SIN(AA)*4.)
   44 IF(CQ)45,45,46
   45 CQ=(0.5*COS(AA)+AB-SIN(AB))/(4.0*SIN(AA))
   46 RB=(T1+234.5)*0.00394*RS
      PRINT3,SS,CC,HC,GE,TS,C1,TT,CW,FS,CP,DF,EL,CF,CM,EC,CQ
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,CK,POL,DI
```

```
PUNCH1,DU,CL,SS,HC,SF,QN
PUNCH1,WL,BK,ZZ,BO,B1,B2
PUNCH1,B3,BS,HO,HX,HY,HZ
PUNCH1,HS,HT,HW,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB
PUNCH1,CE,SH,SD,TT,SK,RB
PUNCH1,TP,D1,FE,RD,RT,COILS
PUNCH1,T2,RR,SNL,WF,PE,SN1
PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
PUNCH1,DR,WR,DY2,TY2,TY,ALY
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH1,G2,DG2,ALG2,AL1,P8
PUNCH1,GE,CS,CF,FS,EC,DF
PUNCH1,RS,GC,PT,C1,CW,CP
PUNCH1,EL,CM,CQ,DW,CC,PBA
PUNCH1,ALZ
PAUSE
END
```

```
C     PASS  2  OUTSIDE COIL LUNDELL
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      DIMENSION DA(8),DX(6),DY(8),DZ(8)
      READ 1,VA,EE,EP,PN,F,PX
      READ 1,RPM,PI,PF,CK,POL,DI
      READ 1,DU,CL,SS,HC,SF,QN
      READ 1,WL,BK,ZZ,BO,B1,B2
      READ 1,B3,BS,HO,HX,HY,HZ
      READ 1,HS,HT,HW,QQ,W,RF
      READ 1,SC,YY,C,TS,SN,DB
      READ 1,CE,SH,SD,TT,SK,RB
      READ 1,TP,D1,FE,RD,RT,COILS
      READ 1,T2,RR,SNL,WF,PE,SN1
      READ 1,DW1,BP1,BP2,TP1,TP2,ALP
      READ 1,DR,WR,DY2,TY2,TY,ALY
      READ 1,P1,P2,P3,P4,P5,P7
      READ 1,G2,DG2,ALG2,AL1,P8
      READ 1,GE,CS,CF,FS,EC,DF
      READ 1,RS,GC,PT,C1,CW,CP
      READ 1,EL,CM,CQ,DW,CC,PBA
      READ 1,ALZ
      DT=DW1
      IF(ZZ-3.0)49,50,51
   49 SM=TT-BS
      GO TO 53
   50 SM=(3.1416*(DI+2.*HS)/QQ)-B3
      GO TO 53
   51 IF(ZZ-4.0)50,52,49
   52 SM=TT-.94*BS
```

```
53 HM=CL+EL
   IF(DT) 61,61,62
61 AC=0.785*DW*DW*SN1
   GO TO 72
62 ZY=0.0
   DA(1)=0.05
   DA(2)=0.072
   DA(3)=0.125
   DA(4)=0.165
   DA(5)=0.225
   DA(6)=0.438
   DA(7)=0.688
   DA(8)=1.5
   DX(1)=0.000124
   DX(2)=0.00021
   DX(3)=0.00021
   DX(4)=0.00084
   DX(5)=0.00189
   DX(6)=0.00189
   DY(1)=0.000124
   DY(2)=0.000124
   DY(3)=0.00084
   DY(4)=0.00084
   DY(5)=0.00189
   DY(6)=0.00335
   DY(7)=0.00754
   DY(8)=0.03020
   DZ(1)=0.000124
   DZ(2)=0.000124
```

```
      DZ(3)=0.000124
      DZ(4)=0.00335
      DZ(5)=0.00335
      DZ(6)=0.00754
      DZ(7)=0.0134
      DZ(8)=0.0302
   63 IF(DT-.05)201,201,200
  200 JA=0
      JB=0
      JC=0
      JD=0
   64 JA=JA+1
      JB=JB+1
      JC=JC+1
      JD=JD+1
      IF(DT-DA(JA))65,65,64
  201 D=0
      IF(ZY)71,71,54
   65 IF(DW-0.188)66,66,67
   66 CY=DX(JB-1)
      CZ=DX(JB)
      GO TO 70
   67 IF(DW-0.75)68,68,69
   68 CY=DY(JC-1)
      CZ=DY(JC)
      GO TO 70
   69 CY=DZ(JD-1)
      CZ=DZ(JD)
   70 D=CY+(CZ-CY)*(DT-DA(JA-1))/(DA(JA)-DA(JA-1))
```

```
      IF(ZY)71,71,54
   71 AC=(DT*DW-D)*SN1
   72 IF(RT)73,73,74
   73 AS=0.785*RD*RD
      GO TO 55
   74 ZY=1.0
      DT=RT
      DW=RD
      GO TO 63
   54 AS=RT*RD-D
   55 S=PI/(C*AC)
      CY=PT    *FE*0.000001/AS
      FK=RR*CY
      FR=(T2+234.5)*FK*0.00394
      RC=0.321*PT    *FE*AS
      IF(SH)202,203,202
  203 ET=1
      EB=1
      GO TO 204
  202 AA=0.584+(SN*SN-1.0)*0.0625*(SD*CL/(SH*HM))**2.0
      AB=(SH*SC*F*AC/(BS*RB))**2.0
      ET=AA*AB*0.00335+1.0
      EB=ET-0.00168*AB
  204 RY=SC*QQ*0.000001*HM/(PN*AC*C*C)
      RG=RS*RY
      RP=RB*RY
      A=PI*SC*CF/(C*TS)
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,CK,POL,DI
```

```
PUNCH1,DU,CL,SS,HC,SF,QN
PUNCH1,WL,BK,ZZ,BO,B1,B2
PUNCH1,B3,BS,HO,HX,HY,HZ
PUNCH1,HS,HT,HW,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB
PUNCH1,CE,SH,SD,TT,SK,RB
PUNCH1,TP,D1,FE,RD,RT,COILS
PUNCH1,T2,RR,SNL,WF,PE,SN1
PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
PUNCH1,DR,WR,DY2,TY2,TY,ALY
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH1,G2,DG2,ALG2,AL1
PUNCH1,GE,CS,CF,FS,EC,DF
PUNCH1,RS,GC,PT,C1,CW,CP
PUNCH1,EL,CM,CQ,DW,CC,PBA
PUNCH1,HM,SM,AS,AC,ET,EB
PUNCH1,S,FK,FR,RC,RG,RP
PUNCH1,A,P8,ALZ
PAUSE
END
```

```
C       PASS  3  OUTSIDE COIL LUNDELL
      1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
        READ 1,VA,EE,EP,PN,F,PX
        READ1 ,RPM,PI,PF,CK,POL,DI
        READ 1,DU,CL,SS,HC,SF,QN
        READ 1,WL,BK,ZZ,BO,B1,B2
        READ 1,B3,BS,HO,HX,HY,HZ
        READ 1,HS,HT,HW,QQ,W,RF
        READ 1,SC,YY,C,TS,SN,DB
        READ 1,CE,SH,SD,TT,SK,RB
        READ 1,TP,D1,FE,RD,RT,COILS
        READ 1,T2,RR,SNL,WF,PE,SN1
        READ 1,DW1,BP1,BP2,TP1,TP2,ALP
        READ 1,DR,WR,DY2,TY2,TY,ALY
        READ 1,P1,P2,P3,P4,P5,P7
        READ 1,G2,DG2,ALG2,AL1
        READ 1,GE,CS,CF,FS,EC,DF
        READ 1,RS,GC,PT,C1,CW,CP
        READ 1,EL,CM,CQ,DW,CC,PBA
        READ 1,HM,SM,AS,AC,ET,EB
        READ 1,S,FK,FR,RC,RG,RP
        READ 1,A,P8,ALZ
        IF(PBA-60.0)105,105,108
    105 IF(CS-0.667)106,106,107
    106 FF=0.25*(6.0*CS-1.0)
    107 FF=0.25*(3.*CS+1.0)
        GO TO 75
    108 IF(CF-0.667)109,109,110
    109 FF=0.05*(24.0*CS-1.0)
```

```
      GO TO 75
  110 FF=0.75
   75 CX=FF/(CF*CF*DF*DF)
      Z=CX*20.0/(PN*QN)
      BT=3.142*DI/QQ-BO
      ZA=BT*BT/(16.0*TS*GC)
      ZB=0.35*BT/TS
      ZC=HO/BO
      ZD=HX*0.333/BS
      ZE=HY/BS
      IF(ZZ-2.0) 76,77,78
   76 PC=Z*(ZE+ZD+ZA+ZB)
      GO TO 82
   77 PC=Z*(ZC+(2.0*HT/(BO+BS))+(HW/BS)+ZD+ZA+ZB)
      GO TO 82
   78 IF(ZZ-4.0) 79,80,81
   79 PC=Z*(ZC+(2.0*HT/(BO+B1))+(2.0*HW/(B1+B2))+(HX*0.333/B2)+ZA+ZB)
      GO TO 82
   80 PC=Z*(ZC+0.62)
      GO TO 82
   81 PC=Z*(ZE+ZD+(0.5*GC/TS)+(0.25*TS/GC)+0.6)
   82 EK=EL/(10.0**(0.103*YY*TS+0.402))
      IF(DI-8.0) 83,83,84
   83 EK=SQRT(EK)
   84 ZF=.612*LOG(10.0*CS)
      EW=6.28*EK*ZF*(TP**(0.62-(0.228*LOG(ZF))))/(CL*DF*DF)
   87 ZA=3.1416*(DI+HS)/QQ
      IF(ZZ-3.0) 88,89,88
   88 TM=ZA-BS
```

```
      GO TO 90
   89 TM=(3.1416*(DI+2.*HS)/QQ)-B3
   90 WI=(TM*QQ*SS*HS+(DU-HC)*3.142*HC*SS)*0.283
      IF(WF)445,446,445
  446 WF=2.52E-6*(DR**2.5)*ALP*RPM**1.5
  445 WC=.321*HM*QQ*AC*SC
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,CK,POL,DI
      PUNCH1,DU,CL,SS,HC,SF,QN
      PUNCH1,WL,BK,ZZ,BO,B1,B2
      PUNCH1,B3,BS,HO,HX,HY,HZ
      PUNCH1,HS,HT,HW,QQ,W,RF
      PUNCH1,SC,YY,C,TS,SN,DB
      PUNCH1,CE,SH,SD,TT,SK,RB
      PUNCH1,TP,D1,FE,RD,RT,COILS
      PUNCH1,T2,RR,SNL,WF,PE,SN1
      PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
      PUNCH1,DR,WR,DY2,TY2,TY,ALY
      PUNCH1,P1,P2,P3,P4,P5,P7
      PUNCH1,HM,SM,AS,AC,ET,EB
      PUNCH1,S,FK,FR,RC,RG,RP
      PUNCH1,G2,DG2,ALG2,AL1
      PUNCH1,GE,CS,CF,FS,EC,DF
      PUNCH1,RS,GC,PT,C1,CW,CP
      PUNCH1,EL,CM,CQ,DW,CC,PBA
      PUNCH1,FF,CX,PC,EK,EW,TM
      PUNCH1,A,WI,WC,P8,ALZ
      PAUSE
      END
```

```
C     PASS  4  OUTSIDE COIL LUNDELL
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      READ1 ,VA,EE,EP,PN,F,PX
      READ1 ,RPM,PI,PF,CK,POL,DI
      READ 1,DU,CL,SS,HC,SF,QN
      READ 1,WL,BK,ZZ,BO,B1,B2
      READ 1,B3,BS,HO,HX,HY,HZ
      READ 1,HS,HT,HW,QQ,W,RF
      READ 1,SC,YY,C,TS,SN,DB
      READ 1,CE,SH,SD,TT,SK,RB
      READ 1,TP,D1,FE,RD,RT,COILS
      READ 1,T2,RR,SNL,WF,PE,SN1
      READ 1,DW1,BP1,BP2,TP1,TP2,ALP
      READ 1,DR,WR,DY2,TY2,TY,ALY
      READ 1,P1,P2,P3,P4,P5,P7
      READ 1,HM,SM,AS,AC,ET,EB
      READ 1,S,FK,FR,RC,RG,RP
      READ 1,G2,DG2,ALG2,AL1
      READ 1,GE,CS,CF,FS,EC,DF
      READ 1,RS,GC,PT,C1,CW,CP
      READ 1,EL,CM,CQ,DW,CC,PBA
      READ 1,FF,CX,PC,EK,EW,TM
      READ 1,A,WI,WC,P8,ALZ
      IF(P1)400,401,400
  401 P1=3.19*BP1*TP1/AL1
  400 IF(P2)402,403,402
  403 AL2=TP-(BP1+BP2)/2.
      P2=3.19*(ALP*(TP2+TP1)/2.)/AL2
  402 IF(P3)404,405,404
```

```
405 R4=AL1+CL/2.
    P3=((3.*BP1+BP2)/4.)*LOG(R4/AL1)*6.28/3.1416
404 IF(P4)409,407,409
407 P4=(3.19*ALP/3.1416)*LOG(1.+(BP1+BP2)/(AL2*2.))
    IF(PX-4.)408,408,409
408 P4=P4*1.5
409 TG=6.E6*EE/(CW*EC*RPM)
    BT1=TG/(QQ*SS*SM)
    FQ=TG*CP/PX
    BC1=FQ/(2.*HC*SS)
    BG1=TG/(3.1416*DI*CL)
    FG=BG1*GE/.00319
    AY2=3.1416*DY2*TY2
    A2=3.1416*DG2*ALG2
    AP=BP2*TP2
    AY=3.1416*TY*(DU+TY)
    WQ=(DU-HC)*1.42*HC*SS*(BC1/BK)**2.0*WL
    WT=  SM   *QQ*SS*HS*0.453*(BT1/BK)**2.0*WL
132 D2=BG1**2.5*0.000061
    D3=(0.0167*QQ*RPM)**1.65*0.000015147
    IF(TS-0.9)133,133,134
133 D4=TS**1.285*0.81
    GO TO 137
134 IF(TS-2.0)135,135,136
135 D4=TS**1.145*0.79
    GO TO 137
136 D4=TS**0.79*0.92
137 D7=BO/GC
    IF(D7-1.7)138,138,139
```

```
138 D5=D7**2.31*0.3
    GO TO 144
139 IF(D7-3.0)140,140,141
140 D5=D7**2.0*0.35
    GO TO 144
141 IF(D7-5.0)142,142,143
142 D5=D7**1.4*0.625
    GO TO 144
143 D5=D7**0.965*1.38
144 D6=10.0**(0.932*C1-1.606)
    BA=3.142*DI*CL
    WN=D1*D2*D3*D4*D5*D6*BA
    PUNCH1,VA,EE,EP,PN,F,PX
    PUNCH1,RPM,PI,PF,CK,POL,DI
    PUNCH1,DU,CL,SS,HC,SF,QN
    PUNCH1,WL,BK,ZZ,BO,B1,B2
    PUNCH1,B3,BS,HO,HX,HY,HZ
    PUNCH1,HS,HT,HW,QQ,W,RF
    PUNCH1,SC,YY,C,TS,SN,DB
    PUNCH1,CE,SH,SD,TT,SK,RB
    PUNCH1,TP,D1,FE,RD,RT,COILS
    PUNCH1,T2,RR,SNL,WF,PE,SN1
    PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
    PUNCH1,DR,WR,DY2,TY2,TY,ALY
    PUNCH1,HM,SM,AS,AC,ET,EB
    PUNCH1,S,FK,FR,RC,RG,RP
    PUNCH1,G2,DG2,ALG2,AL1
    PUNCH1,GE,CS,CF,FS,EC,DF
    PUNCH1,RS,GC,PT,C1,CW,CP
```

```
PUNCH1,EL,CM,CQ,DW,CC,PBA
PUNCH1,FF,CX,PC,EK,EW,TM
PUNCH1,A,WI,WC,WN,WT,WQ
PUNCH1,TG,FQ,BC1,BT1,BG1,FG
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH1,PX,ALP,A2,G2,AY2,AY
PUNCH1,DU,DY2,ALY,PT,FK,AS
PUNCH1,COILS,HC,AP,HS,P8,ALZ
PAUSE
END
```

```
C     PASS  5  OUTSIDE COIL LUNDELL
      DIMENSION AI(90)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
  888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
      K=1
  823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K-89)823,824,824
  824 DO 825 J=1,20
      READ 1,R1,R2,R3,R4,R5,R6
  825 PUNCH1,R1,R2,R3,R4,R5,R6
      READ1 ,TG,FQ,BC1,BT1,BG1,FG
      READ1 ,P1,P2,P3,P4,P5,P7
      READ1 ,PX,ALP,A2,G2,AY2,AY
      READ1 ,DU,DY2,ALY,PT,FK,AS
      READ 1,COILS,HC,AP,HS,P8,ALZ
      LOAD=1
      COREL=3.1416*(DU-HC)/(4.*PX)
      X=BT1
      NA=1
      K=1
      GO TO 802
  806 FT=HS*AT
      X=BC1
      K=2
      NA=1
      GO TO 802
  807 FC=COREL*AT
      FS=FT+FC
```

```
      PL=(2.*(FG+FT)+FC)*(P1+P2+P3+P4)*.001*PX
      PLT=FQ+(PL*2./PX)
      BP=PLT/AP
      X=BP
      NA=31
      K=3
      GO TO 802
  808 FP=ALP*AT
      PL7=.001*P7*(FC+FT+FG+FP)
      PL8=P8*(2.*FG+2.*FT+FC)*.001
      PG2=PLT*PX/2.+PL7+PL8
      BG2=PG2/A2
      FG2=BG2*G2/.00319
      Z=FG2+FP+FG+FT+FC
      IF(COILS-1.)817,818,817
  817 BY=PG2/AY
  821 NA=61
      X=BY
      K=5
      GO TO 802
  810 FY=AT*ALY
      IF(COILS-1.)820,822,820
  820 PL5=.001*P5*(Z+FY)
  818 IF(COILS-1.0)814,815,814
  814 BY2=(PG2+PL5)/AY2
      GO TO 816
  815 BY2=PG2/AY2
  816 X=BY2
      K=4
```

```
      NA=61
      GO TO 802
  809 FY2=((DU-DY2)/6.)*AT
      IF(COILS-1.)822,826,822
  826 PL5=.002*P5*(Z+FY2)
      BY=(PG2+PL5)/AY
      GO TO 821
  822 FNL= (FY+FY2+FG2+FP+FG+FT+FC/2.)*2.
      AINL=FNL/(PT*COILS)
      CD=AINL/AS
      EPNL=AINL*FK*COILS
      PUNCH1,TG,FQ,BC1,BT1,BG1,FG
      PUNCH1,P1,P2,P3,P4,P5,P7
      PUNCH1,A2,AY2,AY,BP,BY,BY2
      PUNCH1,BG2,FG2,FNL,AINL,CD,EPNL
      PUNCH1,AP,PL,PLT,FC,FT,P8
      PUNCH1,PL8,ALZ
      PAUSE
  802 IF(AI(NA)-X)830,831,831
  831 NA=NA+3
  835 IF(AI(NA)-X)833,834,834
  833 NA=NA+2
      GO TO 835
  834 AX=AI(NA)
      BB1=AI(NA-2)
      DC=AI(NA+1)
      D=AI(NA-1)
      XX= (AX-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
      Y=AX-XX*.4343*LOG(DC)
```

```
      AT=EXP(2.306*(X-Y)/XX)
      GO TO (838,839),LOAD
838   GO TO (806,807,808,809,810),K
830   GO TO (836,837),LOAD
836   PRINT 850,
850   FORMAT (17HMACHINE SATURATED)
      PAUSE
      END
```

```
C      PASS  6  OUTSIDE COIL LUNDELL
    3 FORMAT(9X F12.5,2X F12.5)
  870 FORMAT(9X F12.5,2X F12.5/)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      READ1 ,VA,EE,EP,PN,F,PX
      READ1 ,RPM,PI,PF,CK,POL,DI
      READ1 ,DU,CL,SS,HC,SF,QN
      READ1 ,WL,BK,ZZ,BO,B1,B2
      READ1 ,B3,BS,HO,HX,HY,HZ
      READ1 ,HS,HT,HW,QQ,W,RF
      READ1 ,SC,YY,C,TS,SN,DB
      READ1 ,CE,SH,SD,TT,SK,RB
      READ1 ,TP,D1,FE,RD,RT,COILS
      READ1 ,T2,RR,SNL,WF,PE,SN1
      READ1 ,DW1,BP1,BP2,TP1,TP2,ALP
      READ1 ,DR,WR,DY2,TY2,TY,ALY
      READ1 ,HM,SM,AS,AC,ET,EB
      READ1 ,S,FK,FR,RC,RG,RP
      READ1 ,G2,DG2,ALG2,AL1
      READ1 ,GE,CS,CF,FS,EC,DF
      READ1 ,RS,GC,PT,C1,CW,CP
      READ1 ,EL,CM,CQ,DW,CC,PBA
      READ1 ,FF,CX,PC,EK,EW,TM
      READ1 ,A,WI,WC,WN,WT,WQ
      READ1 ,TG,FQ,BC1,BT1,BG1,FG
      READ1 ,P1,P2,P3,P4,P5,P7
      READ1 ,A2,AY2,AY,BP,BY,BY2
      READ1 ,BG2,FG2,FNL,AINL,CD,EPNL
      READ1,AP,PL,PLT,FC,FT,P8
```

```
      READ 1,PL8,ALZ
      XR=.0707*A*DF/(BG1*C1)
      XL=XR*(PC+EW+ALZ)
      XD=90.*EC*PI*CM*DF/(2.*PX*(FG+FG2))
      XQ=CQ*XD/(CM*C1)
      XA=XL+XD
      XB=XL+XQ
      VR=3.1416*DR*RPM/12.
      AGE=((FG+FG2)/(FG))*GE
      PEE=(P1+P2+P3+P4)*PX+P5+P8
      ALF=PEE/CL
      ALA=6.38*DI/(PX*AGE)
      XF=XD*(1.-(C1/CM)/(2.*CP+ALF*1.273/ALA))
      SI=PT*PT*PEE*1.E-8*COILS
      XU=XL+XF
      XS=.88*XU
      XX=XS
      XY=XB
      XN=.5*(XX+XY)
      IF(W)414,415,414
  415 XO=0.
      GO TO 422
  414 IF(CS-1.)417,418,417
  418 AKX=1.
      AKX1=1.
      GO TO 419
  417 AA=(3.*YY/(PN*QN))
      AKX=AA-2.
      IF(AA/3.-.667)420,420,421
```

```
420 AKX1=.75*AA-.25
    GO TO 419
421 AKX1=.75*AA+.25
419 ABL=(AKX/(CF**2))*.07*ALA
    XO=AKX*(ABL+PC)/AKX1
    XO=XR*(XO+(1.667*(HX+3.*HZ))/(PN*QN*CF**2*DF**2*BS)+.2*EW)
422 TC=SI/(FK*COILS)
    RA=PN*PI*PI*RG/(VA*1000.)
    TA=XN/(628.32*F*RA)
    T5=XS*TC/XA
    T4=2./F
    FSC=XA*.02*(FG+FG2)
    SCR=FNL/FSC
    PRINT3,AC,A,S,XR,HM,XL,RG,XD,RP,XQ,ET,XA,EB,XB,PC,XF,EW,SI,WC,XU
    PRINT3,WI,XS,TP,XX,WR,XY,VR,XN,AS,XO,FK,TC,FR,TA,RC,T5,P1,T4
    PRINT3,P2,TG,P3,FQ,P4,BG1,P5,BT1,P7,BC1,P8,FT,FSC,FC
    PRINT870,SCR,FG
    PUNCH1,BO,GC,PI,PN,EP,ET
    PUNCH1,EB,SC,C,XB,XD,PF
    PUNCH1,EE,TG,BT1,FQ,BC1,FG
    PUNCH1,HS,DU,HC,PX,P1,P2
    PUNCH1,P3,P4,P5,P7,BP,ALP
    PUNCH1,BG2,A2,G2,AY2,AY,BY2
    PUNCH1,DY2,BY,ALY,PT,AS,FK
    PUNCH1,XA,RG,WF,WQ,WT,WN
    PUNCH1,SNL,POL,RP,FR,PL,PLT
    PUNCH1,FC,AINL,CD,EPNL,FNL,FT
    PUNCH1,COILS,AP,P8,PL8,CK
    PAUSE
```

END

```
C      PASS  7  OUTSIDE COIL LUNDELL
       DIMENSION GB(4),AE(4),DX(4)
     1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
       READ1 ,BO,GC,PI,PN,EP,ET
       READ1 ,EB,SC,C,XB,XD,PF
       READ1 ,EE,TG,BT1,FQ,BC1,FG
       READ1 ,HS,DU,HC,PX,P1,P2
       READ1 ,P3,P4,P5,P7,BP,ALP
       READ1 ,BG2,A2,G2,AY2,AY,BY2
       READ1 ,DY2,BY,ALY,PT,AS,FK
       READ1 ,XA,RG,WF,WQ,WT,WN
       READ1,SNL,POL,RP,FR,PL,PLT
       READ1 ,FC,AINL,CD,EPNL,FNL,FT
       READ 1,COILS,AP,P8,PL8,CK
       AXX=BO/GC
       IF(AXX-1.)964,965,964
   965 AKSC=2.6
       GO TO 957
   964 IF(AXX-3.75)955,955,956
   955 AKSC=10.**.178/((AXX-1.)**.334)
       GO TO957
   956 AKSC=10.**.11/((AXX-1.)**.174)
   957 XX1=PI*PI*PN
       XX3=3.*EP*PI*PF
       XX2=(ET+EB)/2.-1.
       XX4=AKSC*PI*SC/(C*FG)
       GB(1)=1.
       GB(2)=1.5
       GB(3)=2.
```

```
      GB(4)=POL
      AN=ATAN(SQRT(1.-PF*PF)/PF)
      AN1=SIN(AN)
      DO 777 K=1,4
      YB=GB(K)
      AA    =ATAN((AN1+XB*YB/100.)/PF)
      AE(K)=COS(AA-AN)+XA*SIN(AA)*YB/100.
  777 DX(K)=.93*XD*YB*SIN(AA)/100.
      PUNCH1,AE(1),AE(2),AE(3),AE(4)
      PUNCH1,DX(1),DX(2),DX(3),DX(4)
      PUNCH1,BO,GC,PI,PN,EP,ET
      PUNCH1,EB,SC,C,XB,XD,PF
      PUNCH1,EE,TG,BT1,FQ,BC1,FG
      PUNCH1,HS,DU,HC,PX,P1,P2
      PUNCH1,P3,P4,P5,P7,BP,ALP
      PUNCH1,BG2,A2,G2,AY2,AY,BY2
      PUNCH1,DY2,BY,ALY,PT,AS,FK
      PUNCH1,XA,RG,WF,WQ,WT,WN
      PUNCH1,XX1,XX2,XX3,XX4,SNL,POL
      PUNCH1,RP,FR,PL,PLT,FC,FT
      PUNCH1,AINL,CD,EPNL,FNL,COILS,AP
      PUNCH1,P8,PL8,CK
      PAUSE
      END
```

```
C     PASS  8  OUTSIDE COIL LUNDELL
      DIMENSION AI(90)
      DIMENSION AE(4),DX(4),BPL(4),BYL(4),BY2L(4),BG2L(4),PLL(4),PTLL(4)
      DIMENSION  FFL(4),AIFL(4),CDD(4),EPFL(4)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
  888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
      K=1
  823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K-89)823,824,824
  824 READ1 ,AE(1),AE(2),AE(3),AE(4)
      READ1 ,DX(1),DX(2),DX(3),DX(4)
      READ1 ,BO,GC,PI,PN,EP,ET
      READ1 ,EB,SC,C,XB,XD,PF
      READ1 ,EE,TG,BT1,FQ,BC1,FG
      READ1 ,HS,DU,HC,PX,P1,P2
      READ1 ,P3,P4,P5,P7,BP,ALP
      READ1 ,BG2,A2,G2,AY2,AY,BY2
      READ1 ,DY2,BY,ALY,PT,AS,FK
      READ1 ,XA,RG,WF,WQ,WT,WN
      READ1,XX1,XX2,XX3,XX4,SNL,POL
      READ1,RP,FR,PL,PLT,FC,FT
      READ1 ,AINL,CD,EPNL,FNL,COILS,AP
      READ 1,P8,PL8,CK
      LOAD=2
      DO 900 J=1,4
      AED=AE(J)
      AA=AED*FG+(1.+PF)*FT+FC
      PLL(J)=PL*AA /(FG+FT+FC)
```

```
      P8LL=PLL(J)*PL8/PL
      IF(PF-.95)880,880,881
  881 PR=FQ*CK
      GO TO 882
  880 PR=FQ*(AED-DX(J))
  882 PTLL(J)=PR+(PLL(J)*2./PX)
      X=PTLL(J)/AP
      BPL(J)=X
      NA=31
      K=1
      GO TO 802
  841 FPL= AT* ALP
      PL7L=P7*.001*AA
      PG2L=(PTLL(J)*PX/2.)+PL7L+P8LL
      BG2L(J)=PG2L/A2
      FG2L=BG2L(J)*G2/.00319
      IF(COILS-1.)855,851,855
  855 BYL(J)=PG2L/AY
  859 NA=61
      X=BYL(J)
      K=3
      GO TO 802
  843 FYL=ALY*AT
      IF(COILS-1.)856,857,856
  856 PL5L=P5*.001*(AA+FPL+FYL+FG2L)
  851 IF(COILS-1.)852,853,852
  852 X=(PG2L+PL5L)/AY2
      GO TO 854
  853 X=PG2L/AY2
```

```
854 BY2L(J)=X
    NA=61
    K=2
    GO TO 802
842 FY2L=AT*(DU-DY2)/2.
    IF(COILS-1.)857,858,857
858 PL5L=P5*.002*(AA+FPL+FY2L+FG2L)
    BYL(J)=(PG2L+PL5L)/AY
    GO TO 859
857 FFL(J)=(FG2L+FYL+FPL+FY2L+AA)*2.
    AIFL(J)=FFL(J)/(PT*COILS)
    CDD(J)=AIFL(J)/AS
900 EPFL(J)=AIFL(J)*FR*COILS
837 JA=JA/3
    PUNCH 860,JA
860 FORMAT (I3)
    IF(JA)861,862,861
861 DO 863 J=1,JA
    PUNCH1,PLL(J),PTLL(J),BY2L(J),BYL(J),BG2L(J),BPL(J)
863 PUNCH1,FFL(J),AIFL(J),CDD(J),EPFL(J)
862 PUNCH1,EE,TG,BT1,FQ,BC1,FG
    PUNCH1,HS,DU,HC,PX,P1,P2
    PUNCH1,P3,P4,P5,P7,BP,ALP
    PUNCH1,BG2,A2,G2,AY2,AY,BY2
    PUNCH1,DY2,BY,ALY,PT,AS,FK
    PUNCH1,XA,RG,WF,WQ,WT,WN
    PUNCH1,XX1,XX2,XX3,XX4,SNL,POL
    PUNCH1,RP,FR ,PF,COILS,AP,P8
    PUNCH1,AINL,CD,EPNL,FNL,PL,PLT
```

```
      PAUSE
  802 IF(AI(NA)-X)830,831,831
  831 NA=NA+3
  835 IF(AI(NA)-X)833,834,834
  833 NA=NA+2
      GO TO 835
  834 AX=AI(NA)
      BB1=AI(NA-2)
      DC=AI(NA+1)
      D=AI(NA-1)
      XX= (AX-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
      Y=AX-XX*.4343*LOG(DC)
         AT=EXP(2.306*(X-Y)/XX)
      GO TO (838,839),LOAD
  838 GO TO (806,807,808,809,810),K
  839 JA=JA+1
      GO TO (841,842,843),K
  830 GO TO (836,837),LOAD
  836 PRINT 850,
  850 FORMAT (17HMACHINE SATURATED)
      PAUSE
      END
```

```
C     PASS  9  OUTSIDE COIL LUNDELL
      DIMENSION BPL(4),BG2L(4),FFL(4),AIFL(4),CDD(4),EPFL(4),FCUL(4)
      DIMENSION  WNL(4),STTL(4),SCUL(4),EDDL(4),TOTL(4),PEFF(4),GB(4)
      DIMENSION PLL(4),PTLL(4),BYL(4),BY2L(4)
  961 FORMAT(F11.3,8X F11.3,F11.3,F11.3,F11.3)
  860 FORMAT (I3)
    1 FORMAT (E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      DO 705  N=1,4
      PLL(N)=0
      PTLL(N)=0
      BPL(N)=0
      BG2L(N)=0
      BYL(N)=0
      BY2L(N)=0
      FFL(N)=0
      AIFL(N)=0
      CDD(N)=0
      EPFL(N)=0
      FCUL(N)=0
      WNL(N)=0
      STTL(N)=0
      SCUL(N)=0
      EDDL(N)=0
      TOTL(N)=0
  705 PEFF(N)=0
      READ860,JA
      IF(JA)702,703,702
  702 DO 704 J=1,JA
      READ1 ,PLL(J),PTLL(J),BY2L(J),BYL(J),BG2L(J),BPL(J)
```

```
704 READ1 ,FFL(J),AIFL(J),CDD(J),EPFL(J)
703 READ1 ,EE,TG,BT1,FQ,BC1,FG
    READ1 ,HS,DU,HC,PX,P1,P2
    READ1 ,P3,P4,P5,P7,BP,ALP
    READ1 ,BG2,A2,G2,AY2,AY,BY2
    READ1 ,DY2,BY,ALY,PT,AS,FK
    READ1 ,XA,RG,WF,WQ,WT,WN
    READ1 ,XX1,XX2,XX3,XX4,SNL,POL
    READ1 ,RP,FR ,PF,COILS,AP,P8
    READ1 ,AINL,CD,EPNL,FNL,PL,PLT
    IF(SNL)707,706,707
707 PUNCH1,TG,BT1,FQ,BC1,FG,HS
    PUNCH1,DU,HC,PX,P1,P2,P3
    PUNCH1,P4,P5,P7,AP,ALP,A2
    PUNCH1,G2,AY,AY2,DY2,ALY,COILS
    PUNCH1,EE,P8
706 FEL=AINL*AINL*FK
    TL=FEL+WT+WQ+WN+WF
    ABX=0
    IF(JA)714,712,714
714 IF(JA-4) 708,709,708
709 IF(POL)708,710,708
710 JA=JA-1
708 GB(1)=1.
    GB(2)=1.5
    GB(3)=2.
    GB(4)=POL
    DO 711 K=1,JA
    YB=GB(K)
```

```
      FCUL(K)=AIFL(K)**2*FR*COILS
      STTL(K)=((.0027*XA*YB)**2*2.+1.)*WT
      WNL(K)=((XX4*YB)**2+1.)*WN
      SCUL(K)=XX1*RP*YB
      EDDL(K)=SCUL(K)*XX2
      TOTL(K)=EDDL(K)+SCUL(K)+WNL(K)+STTL(K)+FCUL(K)+WQ+WF
  711 PEFF(K)=XX3*YB*100./(XX3*YB+TOTL(K))
  712 IF(POL)958,959,958
  958 PRINT961,PL,PLL(1),PLL(2),PLL(3),PLL(4)
      PRINT961,PLT,PTLL(1),PTLL(2),PTLL(3),PTLL(4)
      PRINT961,BP,BPL(1),BPL(2),BPL(3),BPL(4)
      PRINT961,BG2,BG2L(1),BG2L(2),BG2L(3),BG2L(4)
      PRINT961,BY2,BY2L(1),BY2L(2),BY2L(3),BY2L(4)
      PRINT961, BY,BYL(1),BYL(2),BYL(3),BYL(4)
      PRINT961,FNL,FFL(1),FFL(2),FFL(3),FFL(4)
      PRINT961,AINL,AIFL(1),AIFL(2),AIFL(3),AIFL(4)
      PRINT961,CD,CDD(1),CDD(2),CDD(3),CDD(4)
      PRINT961,EPNL,EPFL(1),EPFL(2),EPFL(3),EPFL(4)
      PRINT961,WQ,WQ,WQ,WQ,WQ
      PRINT961,WT,STTL(1),STTL(2),STTL(3),STTL(4)
      PRINT961,ABX,SCUL(1),SCUL(2),SCUL(3),SCUL(4)
      PRINT961,ABX,EDDL(1),EDDL(2),EDDL(3),EDDL(4)
      PRINT961,WN,WNL(1),WNL(2),WNL(3),WNL(4)
      PRINT961,FEL,FCUL(1),FCUL(2),FCUL(3),FCUL(4)
      PRINT961,WF,WF,WF,WF,WF
      PRINT961,TL,TOTL(1),TOTL(2),TOTL(3),TOTL(4)
      PRINT961,ABX,PEFF(1),PEFF(2),PEFF(3),PEFF(4)
      PAUSE
  959 PRINT961,PL,PLL(1),PLL(2),PLL(3)
```

```
PRINT961,PLT,PTLL(1),PTLL(2),PTLL(3)
PRINT961,BP,BPL(1),BPL(2),BPL(3)
PRINT961,BG2,BG2L(1),BG2L(2),BG2L(3)
PRINT961,BY2,BY2L(1),BY2L(2),BY2L(3)
PRINT961, BY,BYL(1),BYL(2),BYL(3)
PRINT961,FNL,FFL(1),FFL(2),FFL(3)
PRINT961,AINL,AIFL(1),AIFL(2),AIFL(3)
PRINT961,CD,CDD(1),CDD(2),CDD(3)
PRINT961,EPNL,EPFL(1),EPFL(2),EPFL(3)
PRINT961,WQ,WQ,WQ,WQ
PRINT961,WT,STTL(1),STTL(2),STTL(3)
PRINT961,ABX,SCUL(1),SCUL(2),SCUL(3)
PRINT961,ABX,EDDL(1),EDDL(2),EDDL(3)
PRINT961,WN,WNL(1),WNL(2),WNL(3)
PRINT961,FEL,FCUL(1),FCUL(2),FCUL(3)
PRINT961,WF,WF,WF,WF
PRINT961,TL,TOTL(1),TOTL(2),TOTL(3)
PRINT961,ABX,PEFF(1),PEFF(2),PEFF(3)
PAUSE
END
```

```
C     PASS 10  OUTSIDE COIL LUNDELL
      DIMENSION AI(90)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
  888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
  878 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
  879 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5//)
      K=1
  823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K-89)823,824,824
  824 READ1,TG,BT1,FQ,BC1,FG,HS
      READ1 ,DU,HC,PX,P1,P2,P3
      READ1 ,P4,P5,P7,AP,ALP,A2
      READ1 ,G2,AY,AY2,DY2,ALY,COILS
      READ1,EE,P8
      COREL=3.1416*(DU-HC)/(4.*PX)
      LOAD=1
      YB=.8
      DO 800 N=1,9
      R1=BT1*YB
      R2=FQ*YB
      R3=BC1*YB
      R4=FG*YB
      R5=EE*YB
      X=R1
      NA=1
      K=1
      GO TO 802
  806 FT=HS*AT
```

```
      X=R3
      K=2
      NA=1
      GO TO 802
  807 FC=COREL*AT
      FS=FT+FC
      PL=(2.*(R4+FT)+FC)*(P1+P2+P3+P4)*.001*PX
      PLT=R2+(PL*2./PX)
      BP=PLT/AP
      X=BP
      NA=31
      K=3
      GO TO 802
  808 FP=ALP*AT
      PL7=.001*P7*(FC+FT+R4+FP)
      PL8=P8*(2.*R4+2.*FT+FC)*.001
      PG2=PLT*PX/2.+PL7+PL8
      BG2=PG2/A2
      FG2=BG2*G2/.00319
      Z=FG2+FP+R4+FT+FC
      IF(COILS-1.)817,818,817
  817 BY=PG2/AY
  821 NA=61
      X=BY
      K=5
      GO TO 802
  810 FY=AT*ALY
      IF(COILS-1.)820,822,820
  820 PL5=.001*P5*(Z+FY)
```

```
818 IF(COILS-1.0)814,815,814
814 BY2=(PG2+PL5)/AY2
    GO TO 816
815 BY2=PG2/AY2
816 X=BY2
    K=4
    NA=61
    GO TO 802
809 FY2=((DU-DY2)/6.)*AT
    IF(COILS-1.)822,826,822
826 PL5=.002*P5*(Z+FY2)
    BY=(PG2+PL5)/AY
    GO TO 821
822 FNL=(FY+FY2+FG2+FP+R4+FT+FC/2.)*2.
    PRINT878,R5,R1,FT,R3,FC,R4
    PRINT879,PL,PLT,BP,BY2,BY,FNL
800 YB=YB+.1
    PAUSE
802 IF(AI(NA)-X)830,831,831
831 NA=NA+3
835 IF(AI(NA)-X)833,834,834
833 NA=NA+2
    GO TO 835
834 AX=AI(NA)
    BB1=AI(NA-2)
    DC=AI(NA+1)
    D=AI(NA-1)
    XX= (AX-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
    Y=AX-XX*.4343*LOG(DC)
```

```
      AT=EXP(2.306*(X-Y)/XX)
      GO TO (838,839),LOAD
838   GO TO (806,807,808,809,810),K
839   JA=JA+1
      GO TO (841,842),K
830   GO TO (836,837),LOAD
836   PRINT 850,
850   FORMAT (17HMACHINE SATURATED)
      PAUSE
      END
```

HOMOPOLAR INDUCTOR A-C GENERATOR COMPUTER PROGRAM AND TEST DATA

SECTION PA

HOMOPOLAR COMPUTER DESIGN (INPUT)

MODEL ______________________ EWO ______________________ DESIGN NO(1) ______________________

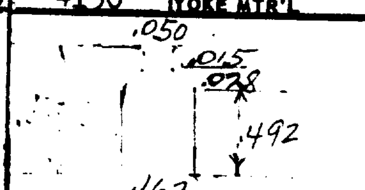
Section	No.	Symbol	Item	Value
PARAMETERS	(2)	KVA	GENERATOR KVA	80
	(3)	E	LINE VOLTS	208
	(4)	E_{ph}	PHASE VOLTS	120
	(5)	m	PHASES	3
	(5a)	f	FREQUENCY	400
	(6)	p	POLES	4
	(7)	RPM	RPM	12000
	(8)	I_{ph}	PHASE CURRENT	223
	(9)	PF	POWER FACTOR	.75
	(9a)	K_c	ADJ. FACTOR	1.0
	(10)		OPTIONAL LOAD POINT	0.0
STATOR STACK	(11)	d	STATOR I.D.	7.5
	(12)	D	STATOR O.D.	10.357
	(13)		GROSS CORE LENGTH	3.31
	(14)	n_v	NO. OF DUCTS	0.0
	(15)	b_v	WIDTH OF DUCT	0.0
	(16)	K_i	STACKING FACTOR (STATOR)	.92
	(19)	k	WATTS/LB.	15
	(20)	B	DENSITY	77.4
STATOR SLOT	(21)		TYPE OF SLOT	2
	(22)	b_o	SLOT OPENING	.050
	(22)	b_1	SLOT WIDTH TOP	0.0
	(22)	b_2		0.0
	(22)	b_3		0.0
	(22)	b_s	SLOT WIDTH	.162
	(22)	h_o		.015
	(22)	h_1		.492
	(22)	h_2		0.0
	(22)	h_3		0.0
	(22)	h_s	SLOT DEPTH	.537
	(22)	h_t		.030
	(22)	h_w		.030
	(23)	Q	NO. OF SLOTS	72
STATOR WINDING	(28)		TYPE OF WDG.	1
	(29)		TYPE OF COIL	1
	(30)	n_s	CONDUCTORS/SLOT	2
	(31)	y	SLOTS SPANNED	13
	(32)	c	PARALLEL CIRCUITS	2
	(33)		STRAND DIA. OR WIDTH	.212
	(34)	N	STRANDS/CONDUCTOR	1.0
	(34a)	N'_{st}	STRANDS/CONDUCTOR	1.0
	(39)		STATOR STRAND T'KNS	.125
	(35)	d	DIA. OF PIN	.50
	(36)	e_2	COIL EXT. STR. PORT	.25
	(37)	h_{st}	UNINS. STRD. HT.	.212
	(38)	h'_{st}	DIST. BTWN. CL OF STD.	.218
	(42a)		PHASE BELT/ANGLE	60
	(40)	sk	STATOR SLOT SKEW	0.0
	(50)	X_s °C	STATOR TEMP °C	200
	(51)	s	RES'TVY STA. COND. @ 20° C	.694
GAP	(59)	g_{min}	MINIMUM AIR GAP	.060
	(59a)	g_{max}	MAXIMUM AIR GAP	.060

Value	Item	No.	Symbol	Section
0.0	FUND/MAX OF FIELD FLUX	(71)	C_1	CONSTANTS
0.0	WINDING CONSTANT	(72)	C_w	
0.0	POLE CONST.	(73)	C_p	
0.0	END EXTENSION ONE TURN	(48)	LE	
0.0	DEMAGNETIZATION FACTOR	(74)	C_m	
0.0	CROSS MAGNETIZING FACTOR	(75)	C_q	
3.88	POLE WIDTH	(76)	b_p	ROTOR STACK
3.425	POLE LENGTH	(76)	ℓ_p	
1.5	POLE HEIGHT	(76)	h_p	
1.25	POLE HEIGHT (EFFECTIVE)	(76)	h'_p	
.67	POLE EMBRACE	(77)	α_c	
7.38	ROTOR DIAMETER	(11a)	d_r	
1.0	STACKING FACTOR (ROTOR)	(16)	Ki	
0	WEIGHT OF ROTOR IRON	(157)	(–)	
7	POLE FACE LOSS FACTOR	(187)	(K1)	
0.0	WIDTH OF SLOT OPENING	(135)	b_{bo}	DAMPER BAR
0.0	HEIGHT OF SLOT OPENING	(135)	h_{bo}	
0.0	DAMPER BAR DIA. OR WIDTH	(136)	( )	
0.0	RECTANGULAR BAR THICKNESS	(137)	h_{bl}	
0.0	RECTANGULAR SLOT WIDTH	(135)	b_{bl}	
0.0	NO. OF DAMPER BARS	(138)	nb	
0.0	DAMPER BAR LENGTH	(139)	ℓ_b	
0.0	DAMPER BAR PITCH	(140)	λ_b	
0.0	RESISTIVITY OF DAMP. BAR @ 20°	(141)	ρ_D	
0.0	DAMPER BAR TEMP °C	(142)	X_o °C	
5.57	SHAFT DIAMETER	(78a)	D_{sh}	SHAFT
0.0	SHAFT I.D.	(78a)	d_{sh}	
3.8	SHAFT EXT. DIAMETER	(78a)	d'_{sh}	
2.6	LENGTH OF SHAFT	(78a)	ℓ_{sh}	
1	TYPE OF YOKE	(78)		YOKE
.60	YOKE THICKNESS	(78)	t_y	
0.0	YOKE THICKNESS	(78)	t_{ye}	
0.0	YOKE THICKNESS	(78)	t_{yr}	
0.0	YOKE I.D.	(78)	d_{yc}	
8.58	FIELD COIL INSIDE DIA.	(78)	d_{coil}	FIELD
10.31	FIELD COIL OUTSIDE DIA.	(78)	D_{coil}	
2.60	FIELD COIL WIDTH	(78)	b_{coil}	
292	NO. OF FIELD TURNS	(146a)	NF	
29.7	MEAN LENGTH OF FLD. TURN	(147)	ℓ_{tr}	
.072	FLD. COND. DIA. OR WIDTH	(148)		
0	FLD. COND. THICKNESS	(149)		
200	FLD. TEMP IN °C	(150)	X_f °C	
.694	RESISTIVITY OF FLD. COND. @20°	(151)	ρ_f	
1.0	NO LOAD SAT.	(87)		
0.0	FRICTION & WINDAGE	(183)	(F&W)	
0.0	LEAKAGE PERMEANCE	(80c)	P_m	PERMEANCE
0.0	LEAKAGE PERMEANCE	(84a)	P_5	
0.0	LEAKAGE PERMEANCE	(85a)	P_6	
0.0	LEAKAGE PERMEANCE	(86a)	P_7	
4130	ROTOR LAM MTR'L	(18)		MATR'L
M-22	STATOR LAM. MTR'L	(18)		
4130	YOKE MTR'L	(18)		

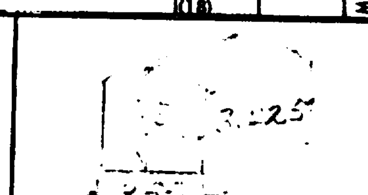
DESIGNER ______________________

DATE ______________________

REV. A

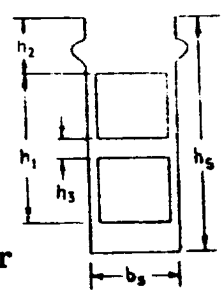


STATOR SLOT



POLE

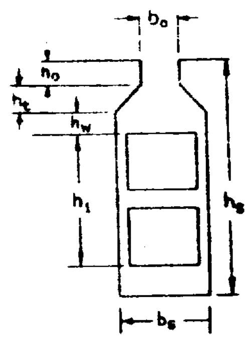
(a) Open Slots



TYPE 1

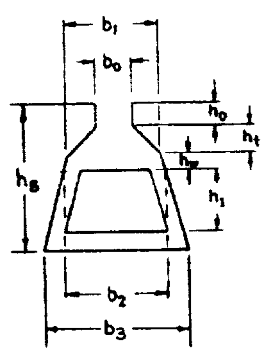
(Type 5 is an open slot with 1 conductor per slot)

(b) Constant Slot Width



TYPE 2

(c) Constant Tooth Width

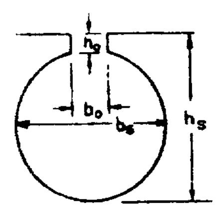


TYPE 3

b_s for type 3 is

$$b_s = \left(\frac{b_1 + b_3}{2}\right)$$

(d) Round Slots



TYPE 4

SUMMARY OF DESIGN CALCULATIONS – HOMOPOLAR INDUCTOR (OUTPUT)

MODEL ______________ EWO ______________ DESIGN NO. ______________

Group	Item	Description	Value	Value	Description	Item	Group
STATOR	(17) (ℓ_s)	SOLID CORE LENGTH	3.04520	1.02570	CARTER COEFFICIENT	(67) (K_s)	GAP
STATOR	(24) (h_c)	DEPTH BELOW SLOT	.89150	78.00015	AIR GAP AREA PER STATOR	(68) (–)	GAP
STATOR	(26) (τ_s)	SLOT PITCH	.32729	194.37944	AIR GAP PERM	(70c) (λ_a)	GAP
STATOR	(27) (τ_s1/3)	SLOT PITCH 1/3 DIST. UP	.34292	.06154	EFFECTIVE AIR GAP	(69) (g_e)	GAP
STATOR	(42) (K_{sk})	SKEW FACTOR	1.00000	1.09909	FUND/MAX OF FLD. FLUX	(71) (C_1)	CONSTANTS
STATOR	(43) (K_d)	DIST. FACTOR	.95613	.42926	WINDING CONST.	(72) (C_w)	CONSTANTS
STATOR	(44) (K_p)	PITCH FACTOR	.90636	.68180	POLE CONST.	(73) (C_p)	CONSTANTS
STATOR	(45) (n_e)	EFF. CONDUCTORS	65.25800	7.74061	END. EXT. ONE TURN	(48) (L_E)	CONSTANTS
STATOR	(46) (a_c)	COND. AREA	.02566	.85350	DEMAGNETIZING FACTOR	(74) (C_M)	CONSTANTS
STATOR	(47) (S_s)	CURRENT DENSITY (STA.)	4345.20000	.42932	CROSS MAGNETIZING FACTOR	(75) (C_q)	CONSTANTS
STATOR	(49) (ℓ_t)	1/2 MEAN TURN LENGTH	11.05000	617.55104	AMP COND/IN	(128) (A)	REACTANCE
STATOR	(53) (R_{ph})	COLD STA. RES. @ 20° C	.00717	.79807	REACTANCE FACTOR	(129) (X)	REACTANCE
STATOR	(54) (R_{SPH})	HOT STA. RES @ X° C	.01227	16.12237	LEAKAGE REACTANCE	(130) (X_ℓ)	REACTANCE
STATOR	(55) (EF_{top})	EDDY FACTOR TOP	2.00020	145.50284	REACTANCE OF	(131) (X_{ad})	REACTANCE
STATOR	(56) (EF_{bot})	EDDY FACTOR BOT	1.14130	66.59649	ARMATURE REACTION	(132) (X_{aq})	REACTANCE
STATOR	(62) (λ_i)	STATOR COND. PERM.	2.71830	161.62521	SYN REACT DIRECT AXIS	(133) (X_d)	REACTANCE
STATOR	(64) (λ_E)	END PERM.	7.38255	82.71886	SYN REACT QUAD AXIS	(134) (X_q)	REACTANCE
STATOR	(65) ( )	WT. OF STA COPPER	26.21200	23.10636	FIELD LEAKAGE REACT	(160) (X_f)	REACTANCE
STATOR	(66) ( )	WT. OF STA IRON	58.27200	.62965	FIELD SELF INDUCTANCE	(161) (L_f)	REACTANCE
PERMEANCE	(80c) (P_m)	LEAKAGE PERMEANCE	46.71117	.00000	DAMPER	(163) (X_{Dd})	REACTANCE
PERMEANCE	(84a) (P_5)	LEAKAGE PERMEANCE	21.05326	.00000	LEAKAGE REACT	(165) (X_{Dq})	REACTANCE
PERMEANCE	(85a) (P_6)	LEAKAGE PERMEANCE	16.69846	39.22873	UNSAT. TRANS. REACT	(166) (X'_{du})	REACTANCE
PERMEANCE	(86a) (P_7)	LEAKAGE PERMEANCE	12.30902	34.52128	SAT. TRANS. REACT	(167) (X'_d)	REACTANCE
ROTOR	(153) (a_{CF})	FLD. COND. AREA	.00406	34.52100	SUB. TRANS.REACT DIRECT AX.	(168) (X''_d)	REACTANCE
ROTOR	(154) (R_F)	COLD FLD RES @ 20° C	1.47900	32.71800	SUB. TRANS.REACT QUAD AX.	(169) (X''_q)	REACTANCE
ROTOR	(155) (R_F)	HOT FLD RES @ X° C	2.53190	58.61950	NEG SEQUENCE REACT	(170) (X_2)	REACTANCE
ROTOR	(156) ( )	WT. OF FLD. COPPER	11.32800	2.39774	ZERO SEQUENCE REACT	(172) (X_o)	REACTANCE
ROTOR	(157) ( )	WT. OF ROTOR IRON	.00000	3712.50000	TOTAL FLUX	(88) (Φ_t)	MAGNETIZATION
ROTOR	(145) (V_r)	PERIPHERAL SPEED	23202.00000	632.80000	FLUX PER POLE	(92) (Φ_p)	MAGNETIZATION
				47.59600	GAP DENSITY	(95) (B_g)	MAGNETIZATION
TIME CONSTANTS	(176) (T_{do})	OPEN CIR. TIME CONST.	.42572	97.91675	TOOTH DENSITY	(91) (B_t)	MAGNETIZATION
TIME CONSTANTS	(177) (T_a)	ARM TIME CONST.	.01018	49.18050	CORE DENSITY	(94) (B_c)	MAGNETIZATION
TIME CONSTANTS	(178) (T'_d)	TRANS TIME CONST.	.09093	40.69794	TOOTH AMPERE TURNS	(97) (F_t)	MAGNETIZATION
TIME CONSTANTS	(179) (T''_d)	SUB TRANS TIME CONST.	.00500	2.56671	CORE AMPERE TURNS	(98) (F_c)	MAGNETIZATION
TIME CONSTANTS	(180) (F_{sc})	SHORT CIR. NI	2968.00000	918.22000	GAP AMPERE TURNS	(96) (F_g)	MAGNETIZATION

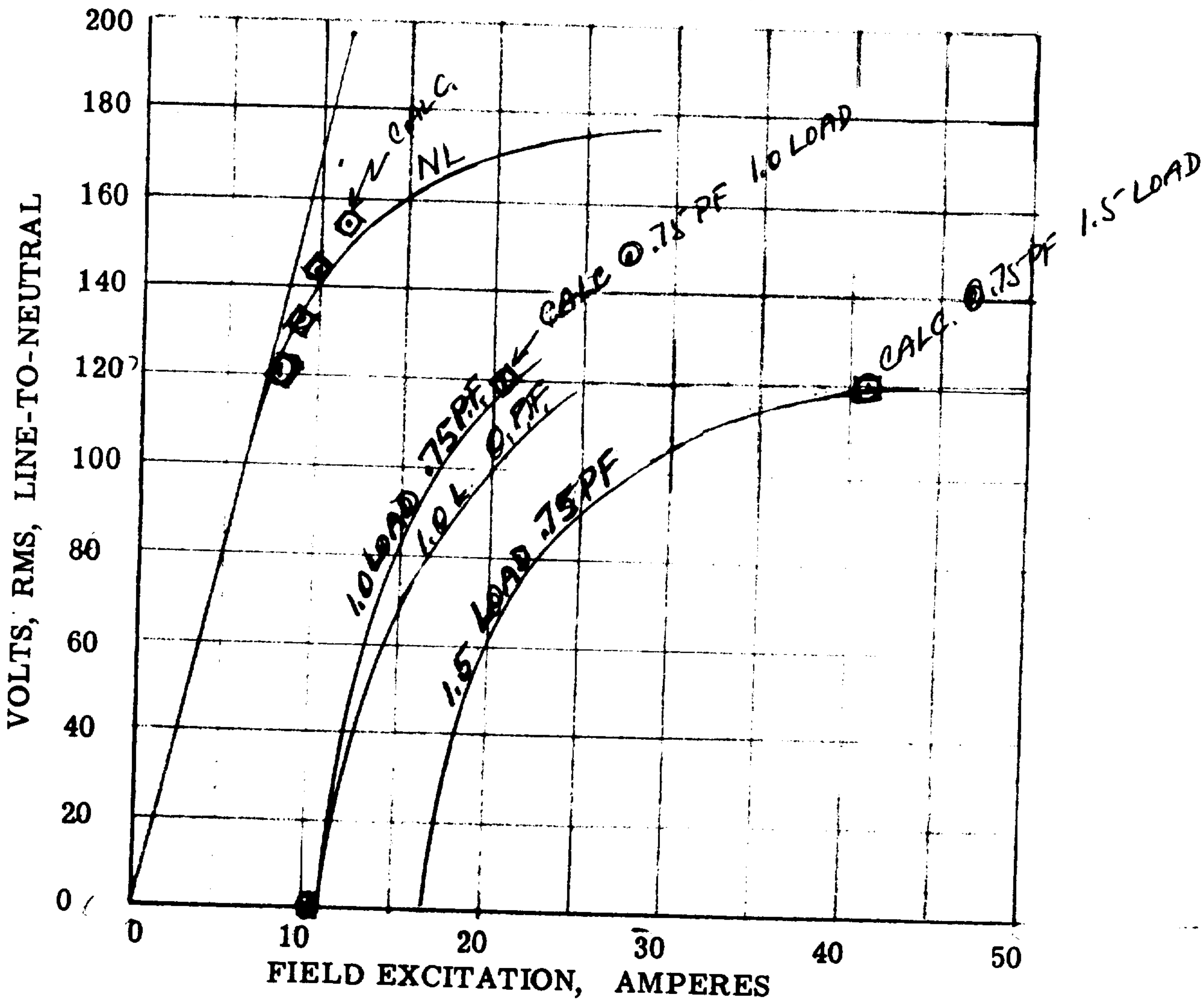
VARIABLE LOAD	PERCENT LOAD	0		100	150	200	OPTIONAL
	(Φ_m) (91a) LEAKAGE FLUX	42.890	Φ_{ml} (202e)	171.764	239.154	307.245	.000
	(F_{g+m})(96a) GAP AMPERE TURNS	960.650	F_{gl} (203)	2348.686	3126.427	3919.002	.000
	(B_p) (104h) POLE DENSITY	50.845	B_{pl} (213b)	68.333	77.910	87.962	.000
	(B_t) (91c) TOOTH DENSITY	97.916	B_{tl} (205)	110.912	117.707	124.574	.000
	(B_{sh}) (113) SHAFT DENSITY	59.465	B_{shl} (215a)	89.907	106.319	123.341	.000
	(B_c) (94) CORE DENSITY	49.180	B_{cl} (200g)	69.633	80.139	91.529	.000
	(B_{yc}) (125a) COIL YOKE DENSITY	73.591	B_{ycl} (228a)	115.486	138.154	.000	.000
	(F_{nl}) (127) TOTAL NI	2199.800	(F_{fl}) (236)	6016.900	11967.000	.000	.000
	(I_{fnl}) (127a) FIELD AMPS	7.533	(I_{fl}) (237)	20.605	40.982	.000	.000
	(S_F) (127c) CUR.DENS.(FLD.)	11.142	(S_{fl}) (239)	52.171	103.764	.000	.000
	(E_F) (127b) FIELD VOLTS	1851.270	(E_{fl}) (238)	5063.601	10070.987	.000	.000
	(I^2R_f) (182) FIELD LOSS	83.939	(I^2R_f) (241)	1075.044	4252.569	.000	.000
	(F&W) (183) F&W LOSS	1678.700	(F&W) (183)	1678.700	1678.700	1678.700	1678.700
	(W_{tnl}) (184) STA TOOTH LOSS	231.640	(W_{tl}) (242)	430.804	646.878	.000	.000
	(W_c) (185) STA CORE LOSS	220.980	(W_c) (185)	443.002	586.764	.000	.000
	(W_{pnl}) (186) POLE FACE LOSS	571.680	(W_{pfl}) (243)	799.610	1084.524	.000	.000
	(W_{dnl}) (193) DAMPER LOSS	.000	(W_{dfl}) (244)	.000	.000	.000	.000
	(I^2R_s) (194) STATOR CU LOSS	.000	(I^2R_s) (245)	1831.700	4121.325	.000	.000
	(–) (195) EDDY LOSS	.000	(–) (246)	1045.442	2352.246	.000	.000
	(–) (196) TOTAL LOSSES	2786.939	(–) (247)	7304.304	14723.007	.000	.000
	(–) (–) RATING (KW)	.000	(–) (248)	60.210	90.315	.000	.000
	(–) (–) PERCENT EFF.	.000	(–) (251)	89.181	85.983	.000	.000

HOMOPOLAR

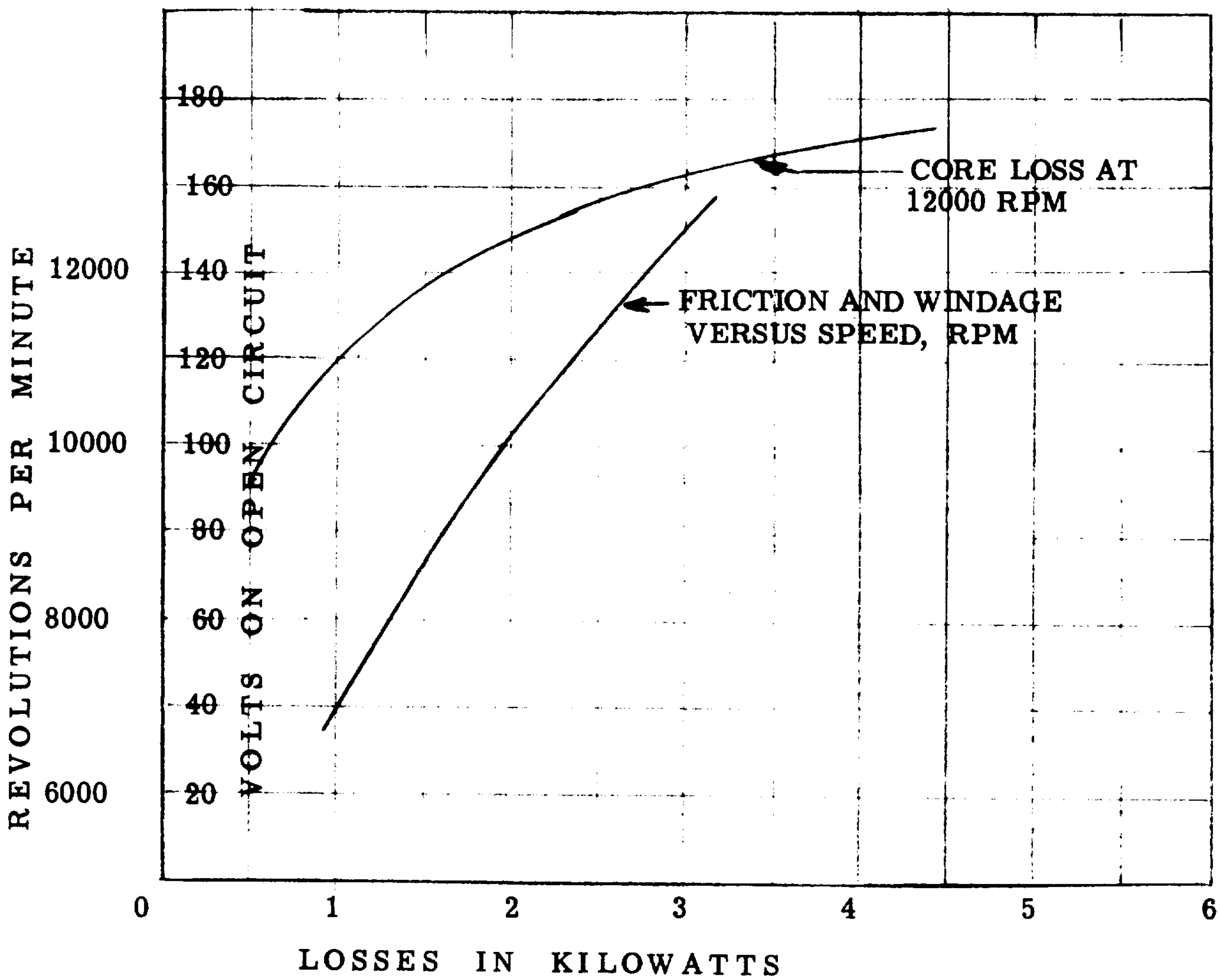
NO LOAD SATURATION OUTPUT SHEET

ITEMS / VOLTS	(3) (E) VOLTS (104b) (B_p) POLE DENSITY	(96a) (F_{gm}) AIR GAP A.T. (106a) (F_p) POLE A.T.	(94) (B_c) CORE DENSITY (113) (B_{SH}) SHAFT DENSITY	(98) (F_c) CORE A.T. (114) (F_{SH}) SHAFT A.T.	(91) (B_t) TOOTH DENSITY (125a) (B_{YC}) YOKE DENSITY	(97) (F_t) TOOTH A.T. (127) (F_{nl}) TOTAL A.T. (N.L.)
80%	166.27200 50.20037	768.52306 44.36387	48.55613 57.96235	2.51178 77.68069	78.33340 71.13030	4.9913 1742.0747
90%	187.05600 50.52312	864.58844 44.38257	48.86832 58.71500	2.53909 77.75708	88.12507 72.36169	11.3575 1947.8840
100%	207.84000 50.84588	960.65383 44.40128	49.18050 59.46763	2.56671 77.83353	97.91675 73.59307	40.6979 2199.89540
110%	228.62400 51.16864	1056.71920 44.42000	49.49269 60.22027	2.59462 77.91005	107.70842 74.82445	95.8777 2503.63030
120%	249.40800 51.49139	1152.78450 44.43872	49.80487 60.97292	2.62284 77.98666	117.50010 76.05584	193.67678 2892.64930
130%	270.19200 51.81415	1248.84990 44.45745	50.11705 61.72556	2.65137 78.06333	127.29177 77.28722	388.32247 3475.4099
140%	MACHINE SATURATED					
150%						
160%						

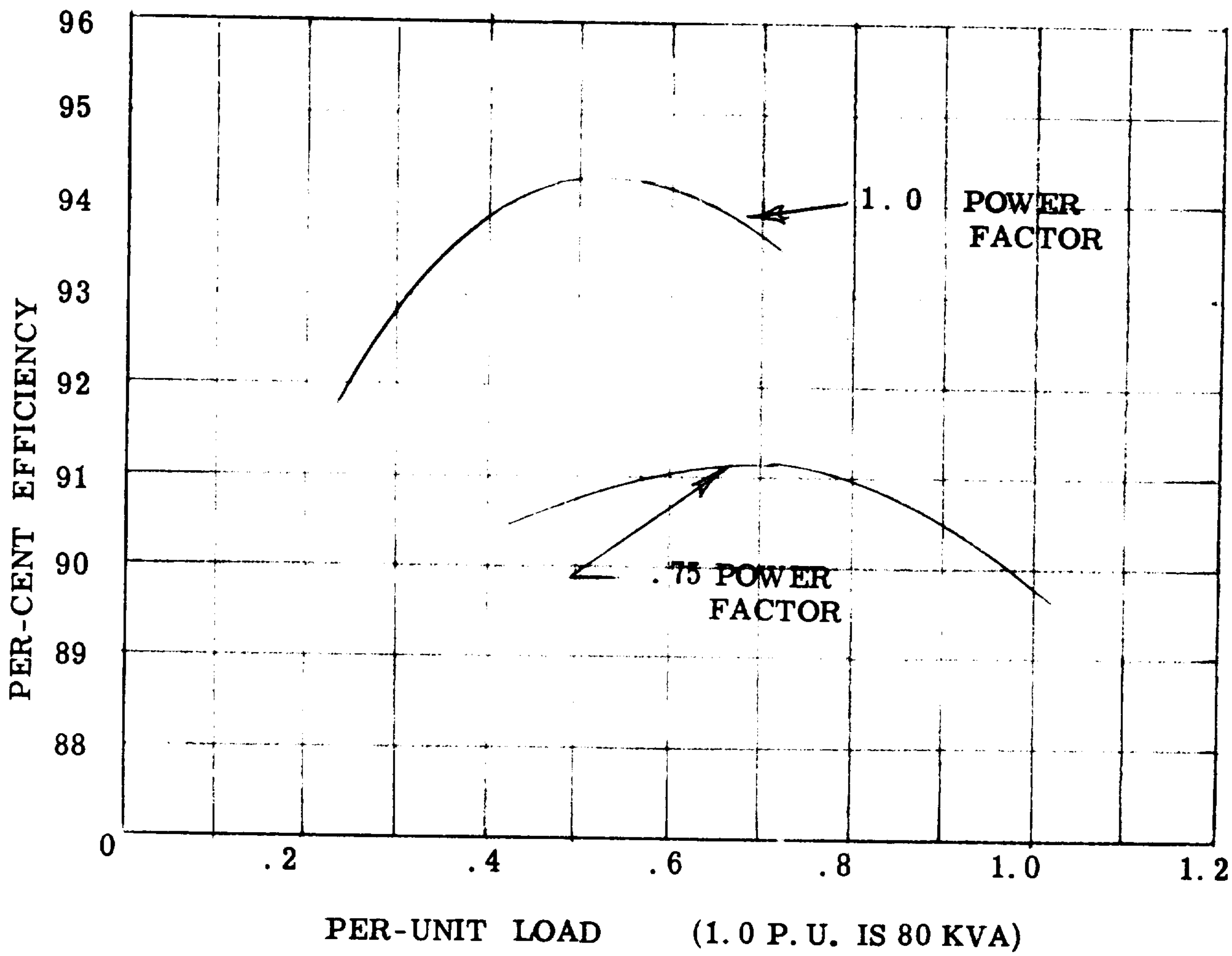
TEST SATURATION CURVES AND CALCULATED SATURATION POINTS FOR A 12000 RPM, 80 KVA, 400 CPS, HOMOPOLAR INDUCTOR

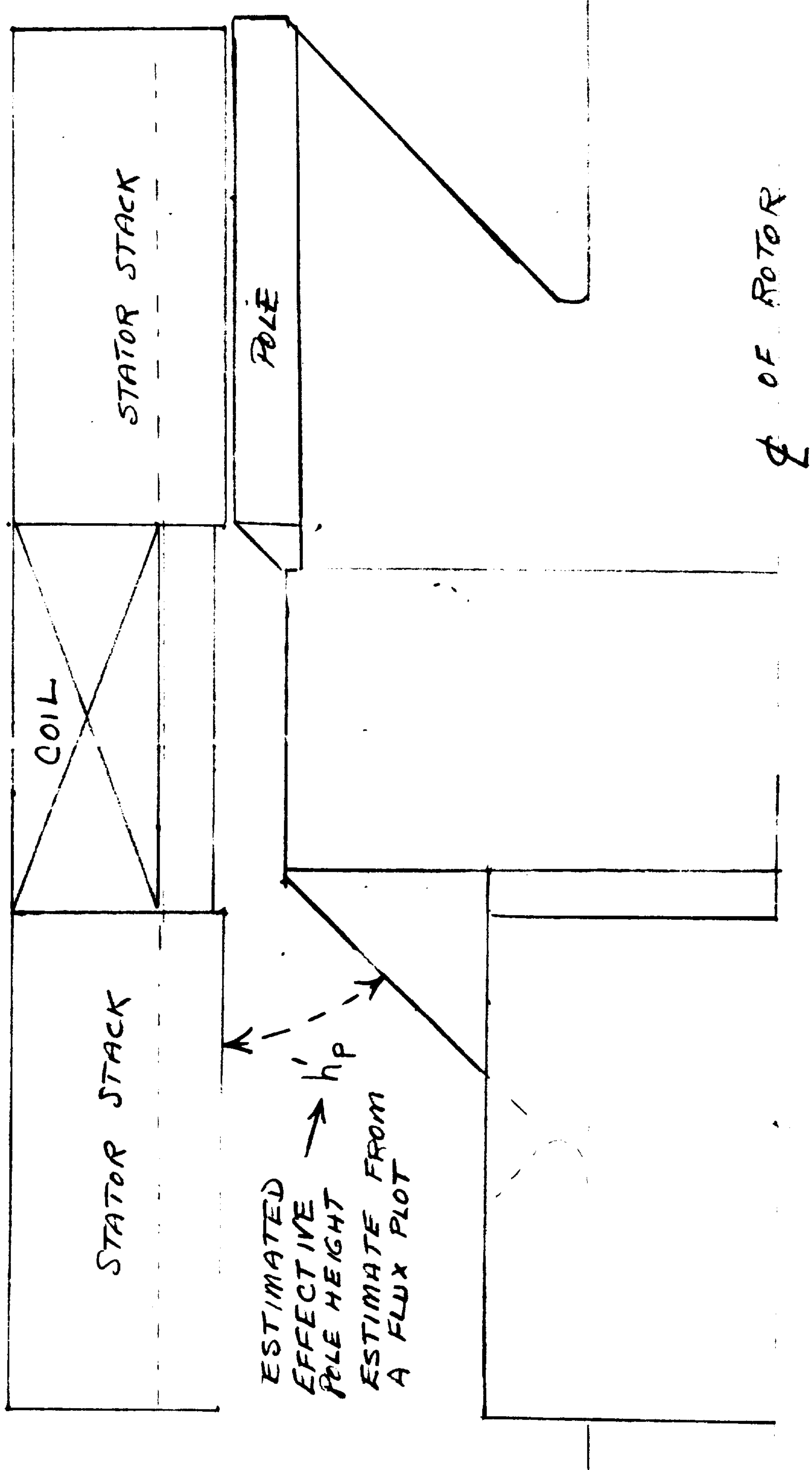


TEST VALUES OF LOSSES FOR A 12000 RPM, 80 KVA, 400 CPS, HOMOPOLAR INDUCTOR A-C GENERATOR



TEST EFFICIENCY VALUES FOR A 12000 RPM, 80 KVA, 400 CPS, HOMOPOLAR INDUCTOR, A-C GENERATOR




STATOR STACK
POLE
COIL
STATOR STACK
℄ OF ROTOR
h_p'
ESTIMATED EFFECTIVE POLE HEIGHT
ESTIMATE FROM A FLUX PLOT

COMPUTER PROCEDURE FOR

HOMOPOLAR DESIGN CALCULATIONS

1. Clear core (no switch control).

2. Insert output Form #1 into typewriter, set margin for correct output, and set typewriter for single space.

3. Load pass #1 followed by input parameters (output punched cards).

4. Reset and Load pass #2 followed by output from pass #1 (output printed plus punched cards).

5. Reset and Load pass #3 followed by output from pass #2 (output printed plus punched cards).

6. Reset and Load pass #4 followed by output from pass #3 (output printed plus punched cards).

7. Reset and Load pass #5 followed by output from pass #4 (output printed plus punched cards).

8. Reset and Load pass #6 followed by saturation curve values* and output from pass #5 (output printed and punched cards).

9. Reset and Load pass #6A followed by output from pass #6 (output punched cards).

10. Reset and Load pass #7 followed by output from pass #6A (output punched cards).

11. Reset and Load pass #8 followed by saturation curve values* and output from pass #7 (output printed and punched cards).

12. Reset and Load pass #9 followed by output from pass #8 (output printed plus punched cards if no load saturation curve required).

13. If there is punched card output from pass #9, a no load saturation curve is required. Insert output Form #2 into typewriter and reset margin. Load pass #10 followed by saturation curve values* and output from pass #9 (output printed).

* Saturation curve values are loaded in order shown on Input Form #1.

ALL INPUT PARAMETERS ARE IN FORMAT F7.0 (FIG. 1)

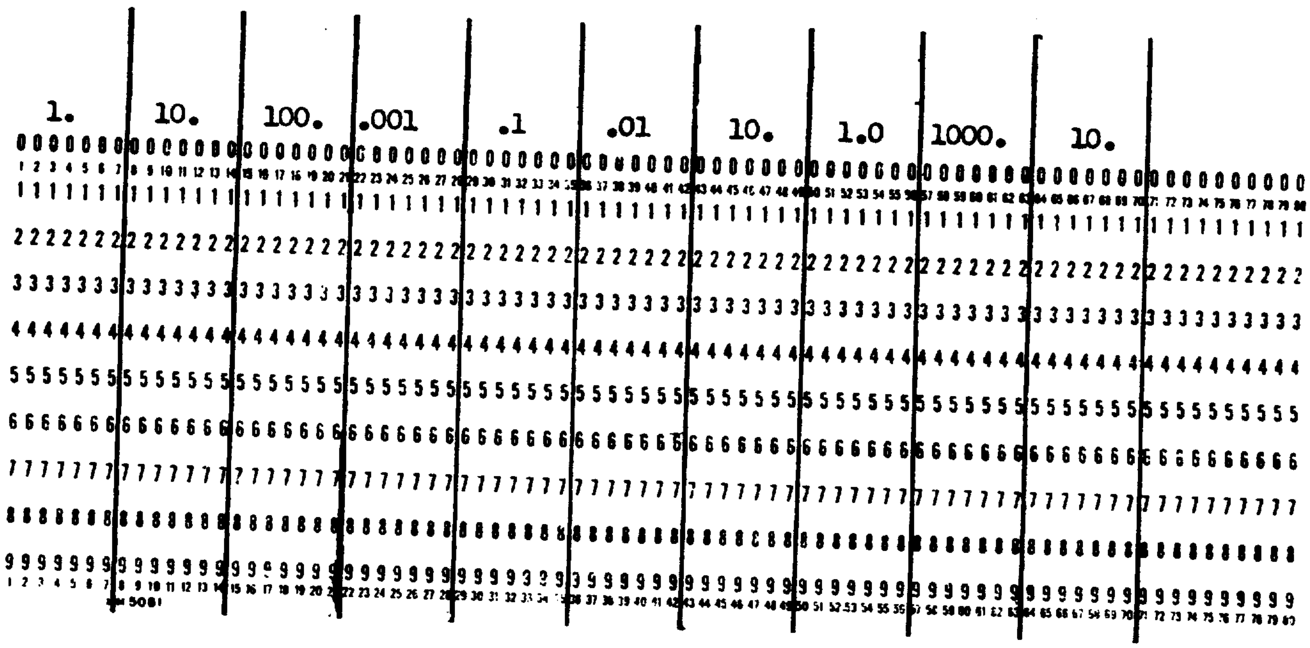


FIG. 1

ALL SATURATION CURVE VALUES ARE IN FORMAT F10.0 (FIG. 2)
(ALL SATURATION CURVES MUST HAVE 5 CARDS)

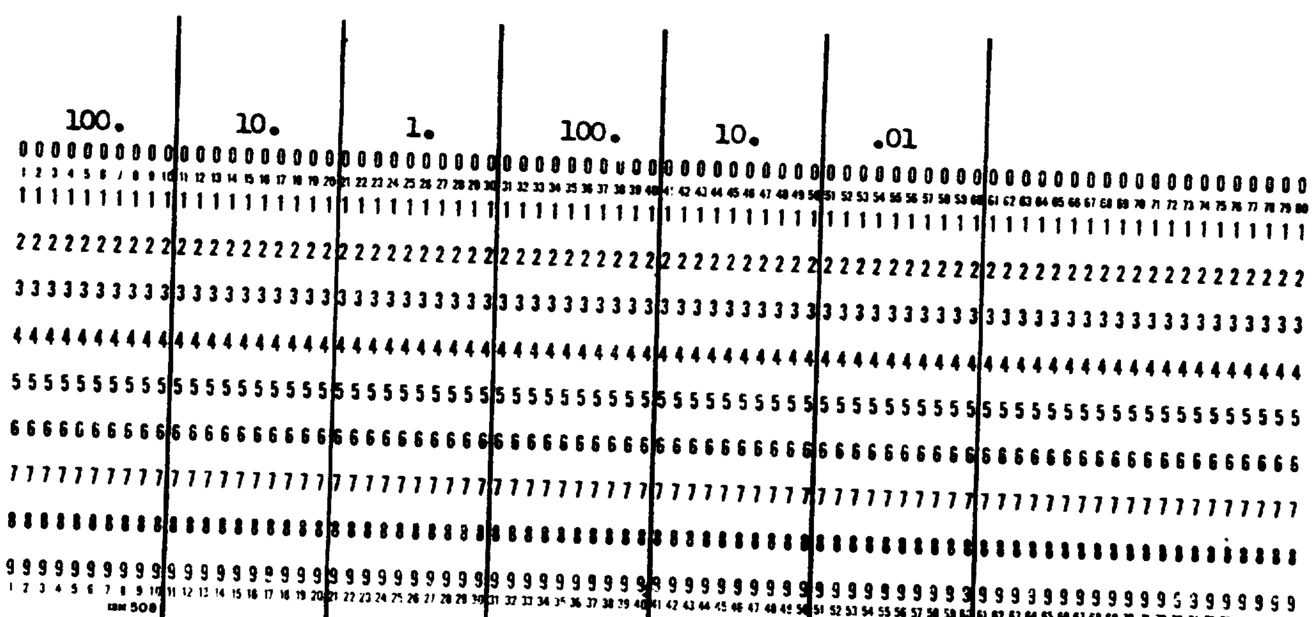


FIG. 2

HOMOPOLAR INDUCTOR

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	A, a	
(46)	A_c	AC
(68)	A_g	GA
(79)	A_p	AP
(128)	A	A
(91b)	AT	ATH
(94a)	A_c	ACR
(112)	A_{sh}	ASH
(124a)	A_y	AY
(124b)	A_{yc}	AYC
(124c)	A_{yr}	AYR
(144)	A_{cd}	AB
(153)	A_{cf}	AS
	B, b	
(15)	b_v	BV
(20)	B	BK
(22)	b_o	BO
(22)	b_1	B1
(22)	b_2	B2
(22)	b_3	B3
(22)	b_s	BS
(57)	b_{tm}	TM
(57a)	$b_{t\ 1/3}$	SM
(76)	b_p	BP

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(78)	b_{coil}	BCOIL
(91)	B_t	BT
(91c)	B'_t	BT
(94)	B_c	BC
(95)	B_g	BG
(104b)	B_p	BP
(113)	B_{sh}	BSH
(125a)	B_{yc}	BYC
(126a)	B_y	BY
(135)	b_{bo}	WO
(135)	b_{bl}	B
(200b)	B_{pL}	BPL
(200g)	B_{CL}	BCL
(202c)	B'_{shL}	BSHL
(205)	B_{TL}	BTL
(213b)	B_{PL}	BPL
(215a)	B_{SHL}	BSHL
(228a)	B_{YCL}	BYCL
(229a)	B_{YL}	BYL

C, c

(32)	C	C
(60)	C_x	CX
(71)	C_1	C1

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(72)	C_w	CW
(73)	C_p	CP
(74)	C_m	CM
(75)	C_q	CQ
	D, d	
(11)	d	DI
(11a)	d_r	DR
(12)	D	DU
(35)	d_b	DB
(78)	d_{yc}	DYC
(78)	d_{coil}	PCOIL
(76)	D_{coil}	DCOIL
(78a)	d'_{sh}	DISH
(78a)	d_{sh}	DSH
	E, e	
(3)	E	EE
(4)	E_{ph}	EP
(55)	EF_{top}	ET
(56)	$E_F B_{ot}$	EB
(127)	E_f	EF
(198)	e_d	ED
(238)	E_{FFL}	EF

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	F, f	
(5a)	f	F
(96)	F_g	FH
(96a)	F_g+M	FGM
(97)	F_T	FT
(98)	F_c	FC
(106a)	F_p	FP
(114)	F_{SH}	FSH
(125b)	F_{yc}	FYC
(125d)	F_{yr}	FYR
(126b)	F_y	FY
(127)	F_{NL}	FNL
(180)	F_{sc}	FSC
(183)	F & W	WF
(198b)	F_{dm}	FGML
(199)	F_g'L	FGL
(200)	F'_{TL}	FTL
(200c)	F'_{PL}	FPL
(201)	F_{CL}	FCL
(202d)	F_{SHL}	FSHL
(203)	F_{GL}	FGL
(206)	F_{TL}	FTL
(213L)	F_{PL}	FPL
(216a)	F_{SHL}	FSHL

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(228b)	F_{ycL}	FYCL
(228d)	F_{yrL}	FYRL
(229b)	F_{yL}	FYL
(236)	F_{FL}	FFL
	G, g	
(59)	g	GC
(69)	g_e	GE
	H, h	
(22)	h_o	HO
(22)	h_1	HX
(22)	h_2	HY
(22)	h_3	HZ
(22)	h_s	HS
(22)	h_t	HT
(22)	h_w	HW
(24)	h_c	HC
(37)	h_{st}	SH
(38)	h'_{st}	SD
(76)	h_p	HP
(76)	h'_p	HP1
(135)	h_{bo}	HD
(135)	h_b	DD
(137)	h_{b1}	H

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	I, i	
(8)	I_{PH}	PI
(127a)	I_{FNL}	FI
(182)	I^2R_F	PR
(237)	I_{FFL}	FI
(241)	I^2R_F	PR
	K, k	
(2)	K_{VA}	VA
(9a)	K_c	CK
(16)	K_i	RK
(19)	k	WL
(42)	K_{SK}	FS
(43)	K_d	DF
(44)	K_p	CF
(61)	K_x	FF
(63)	K_E	EK
(67)	K_s	CC
	L, l	
(13)	l	L
(17)	l_s	SS
(36)	l_{e2}	CE
(48)	L_E	EL
(49)	l_t	HM

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(76)	l_p	PL
(139)	l_b	SB
(147)	l_{tf}	FE
(161)	L_F	SI
	M, m	
(5)	m	PN
	N, n	
(14)	n_v	HV
(30)	n_s	SC
(34)	N_{st}	SN
(34a)	N'_{st}	SN1
(45)	n_e	EC
(138)	n_b	BN
(146)	N_F	PT
	O, o	
	P, p	
(6)	p	PX
(9)	P_F	PF
(80c)	P_m	PM
(84a)	P_5	P5
(85a)	P_6	P6
(86a)	P_7	P7

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	Q, q	
(23)	Q	QQ
(25)	q	QN
	R, r	
(7)	R_{PM}	RPM
(53)	R_{SPH}	RG
(54)	R_{SPH} (HOT)	RP
(154)	R_f (COLD)	FK
(155)	R_f (HOT)	FR
	S, s	
(127c)	S_F	CDD
(181)	S_{CR}	SCR
(239)	S_{FL}	CDD
	T, t	
(78)	t_{yr}	TYR
(78)	t_{yc}	TYE
(78)	t_y	TY
(176)	T'_{do}	TC
(177)	T_a	TA
(178)	T'_d	T5
(179)	T''_d	T4

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	U, u	
	V, v	
(145)	V_r	VR
	W, w	
(184)	WTNL	ST
(185)	W_C	WQ
(186)	W_{NPL}	WN
(193)	W_{DNL}	WD
(242)	W_{TFL}	ST
(243)	W_{PFL}	PP
(244)	W_{DFL}	DL
	X, x	
(50)	$X_s\,^oC$	T1
(129)	X	XR
(130)	X_L	XL
(131)	X_{ad}	XD
(132)	X_{aq}	XQ
(133)	X_d	XA
(134)	X_q	XB
(142)	$X_D\,^oC$	T3
(150)	$X_C\,^oC$	T2

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(160)	X_F	XF
(163)	X_{Dd}	X1
(165)	X_{Dq}	X2
(166)	$X'D_u$	XU
(167)	X'_d	XS
(168)	X''_d	XX
(169)	X'''_q	XY
(170)	X_2	XN
(172)	X_o	XO
	Y, y	
(31)	y	YY
	Υ	
(26)	Υ_s	TS
(27)	$\Upsilon_{s1/3}$	TT
(40)	Υ_{sk}	SK
(41)	Υ_p	TP
(140)	Υ_b	TB
	λ	
(62)	λ_i	PC
(64)	λ_E	EW
(70c)	λ_a	AG

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	ϕ	
(88)	ϕ_T	TG
(91a)	ϕ_m	PHM
(92)	ϕ_p	FQ
(99)	ϕ_7	PH7
(112a)	ϕ_{SH}	PSH
(118a)	ϕ_5	PH5
(121a)	ϕ_6	PH6
(198c)	ϕ_{mL}	PML
(200a)	ϕ'_{PL}	PPL
(200d)	ϕ'_{5L}	PH5L
(200e)	ϕ_{bL}	PH6L
(200f)	ϕ_{CL}	PCL
(202)	ϕ'_{7L}	PH7L
(202b)	ϕ'_{SHL}	PSHL
(202e)	ϕ_{mL}	PML
(207a)	ϕ_{7L}	PH7L
(213)	ϕ_{PL}	PPL
(214a)	ϕ_{SHL}	PSHL
(220a)	ϕ_{6L}	PH6L
(226a)	ϕ_{5L}	PH5L
	ρ	
(51)	ρ_s	RS
(141)	ρ_D	RE
(151)	ρ_F	RR

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	$\underline{\alpha}$	
(77)	α	PE
	$\underline{\theta}$	
(198a)	θ	AN
	$\underline{K}$	
(187)	K_1	D1
(188)	K_2	I
(189)	K_3	D3
(190)	K_4	D4
(191)	K_5	D5
(192)	K_6	D6

```
C       PASS 1 HOMOPOLAR INDUCTOR
        DIMENSION DA(8),DX(6),DY(8),DZ(8)
      1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      2 FORMAT(F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0)
     33 READ2,VA,EE,EP,PN,F,PX,RPM,PI,PF,CK
        READ2,POL,DI,DU,CL,HV,BV,SF,WL,BK,ZZ
        READ2,B0,B1,B2,B3,BS,H0,HX,HY,HZ,HS
        READ2,HT,HW,QQ,W,RF,SC,YY,C,DW,SN
        READ2,SN1,DW1,DB,CE,SH,SD,PBA,SK,T1,RS
        READ2,GC,GP,C1,CW,CP,EL,CM,CQ,BP,PL
        READ2,HP,HP1,PE,DR,RK,WR,D1,WO,HD,DD
        READ2,H,B,BN,SB,TB,RE,T3,DSH,DISH,DISH1
        READ2,ALH,TYPY,TY,TYE,TYR,DYC,PCOIL,DCOIL,BCOIL,PT
        READ2,FE,RD,RT,T2,RR,SNL,WF,PM,P5,P6
        READ2,P7
        SS=SF*(CL-HV*BV)
        HC=(DU-DI-2.0*HS)*0.5
        ZY=0.7*HS
        IF(HC-ZY) 33,33,5
      5 QN=QQ/(PX*PN)
        TS=3.142*DI/QQ
        IF(ZZ-4.0)29,30,29
     29 TT=(0.667*HS+DI)*3.142/QQ
        GO TO 31
     30 TT=3.1416*(DI+2.*H0+1.32*BS)/QQ
     31 IF(ZZ-1.0)6,6,7
      6 B0=BS
        CC=(5.0*GC+BS)*TS/((5.0*GC+BS)*TS-BS*BS)
        GO TO 8
```

```
  7 QC=(4.44*GC+0.75*BO)*TS
    CC=QC/(QC-BO*BO)
  8 CS=YY/(PN*QN)
    TP=3.142*DI/PX
    IF(SK)32,32,92
 32 FS=1.0
    GO TO 34
 92 FS=SIN(1.571*SK/TP)*TP/(1.571*SK)
 34 IF(PBA-60.)9,9,10
  9 D=1.0
    GO TO 95
 10 D=2.0
 95 I=QN
    U=I
    IF(QN-U)36,36,35
 35 U=PX*PN
    XX=U
    N=U
    DO 11 K=1,N
    Z=U/XX
    I=Z
    Z1=I
    IF(Z-Z1)12,12,11
 12 ZY=QQ/XX
    I=ZY
    Z1=I
    IF(ZY-Z1)37,37,11
 11 XX=XX-1.
 36 ZY=QN
```

```
37 DF=SIN(1.571*D/PN)/(ZY*D*SIN(1.571/(PN*ZY)))
   CF=SIN(YY*1.571/(PN*QN))
   EC=QQ*SC*CF*FS/C
   DT=DW1
   IF(DT) 13,13,14
13 AC=0.785*DW*DW*SN1
   GO TO 24
14 ZY=0.0
   DA(1)=0.05
   DA(2)=0.072
   DA(3)=0.125
   DA(4)=0.165
   DA(5)=0.225
   DA(6)=0.438
   DA(7)=0.688
   DA(8)=1.5
   DX(1)=0.000124
   DX(2)=0.00021
   DX(3)=0.00021
   DX(4)=0.00084
   DX(5)=0.00189
   DX(6)=0.00189
   DY(1)=0.000124
   DY(2)=0.000124
   DY(3)=0.00084
   DY(4)=0.00084
   DY(5)=0.00189
   DY(6)=0.00335
   DY(7)=0.00754
```

```
      DY(8)=0.03020
      DZ(1)=0.000124
      DZ(2)=0.000124
      DZ(3)=0.000124
      DZ(4)=0.00335
      DZ(5)=0.00335
      DZ(6)=0.00754
      DZ(7)=0.0134
      DZ(8)=0.0302
   93 IF(DT-.05)94,94,15
   15 JA=0
      JB=0
      JC=0
      JD=0
   16 JA=JA+1
      JB=JB+1
      JC=JC+1
      JD=JD+1
      IF(DT-DA(JA))17,17,16
   94 D=0
      IF(ZY)23,23,27
   17 IF(DW-0.188)18,18,19
   18 CY=DX(JB-1)
      CZ=DX(JB)
      GO TO 22
   19 IF(DW-0.75)20,20,21
   20 CY=DY(JC-1)
      CZ=DY(JC)
      GO TO 22
```

```
21 CY=DZ(JD-1)
   CZ=DZ(JD)
22 D=CY+(CZ-CY)*(DT-DA(JA-1))/(DA(JA)-DA(JA-1))
   IF(ZY)23,23,27
23 AC=(DT*DW-D)*SN1
24 IF(RT)25,25,26
25 AS=0.785*RD*RD
   GO TO 28
26 ZY=1.0
   DT=RT
   DW=RD
   GO TO 93
27 AS=RT*RD-D
28 S=PI/(C*AC)
   PUNCH1,VA,EE,EP,PN,F,PX
   PUNCH1,RPM,PI,PF,CK,POL,DI
   PUNCH1,DU,CL,SS,HC,SF,QN
   PUNCH1,WL,BK,ZZ,BO,B1,B2
   PUNCH1,B3,BS,HO,HX,HY,HZ
   PUNCH1,HS,HT,HW,QQ,W,RF
   PUNCH1,SC,YY,C,TS,SN,DB
   PUNCH1,CE,SH,SD,TT,SK,T1
   PUNCH1,RS,GC,GP,C1,CW,CP
   PUNCH1,EL,CM,CQ,BP,PL,HP
   PUNCH1,PE,DR,RK,CC,WR,D1
   PUNCH1,WO,HD,DD,H,B,BN
   PUNCH1,SB,TB,RE,T3,DSH,DISH
   PUNCH1,ALH,TYPY,PCOIL,DCOIL,BCOIL,TY
   PUNCH1,TYE,TYR,DYC,PT,FE,RD
```

```
PUNCH1,RT,T2,RR,SNL,WF,CS
PUNCH1,AS,FS,TP,DF,CF,EC
PUNCH1,AC,S,HP1,DISH1,PM,P5
PUNCH1,P6,P7,PBA
PAUSE
END
```

```
C     PASS 2 HOMOPOLAR INDUCTOR
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    3 FORMAT(9X F12.5,2X F12.5)
      READ 1,VA,EE,EP,PN,F,PX
      READ 1,RPM,PI,PF,CK,POL,DI
      READ 1,DU,CL,SS,HC,SF,QN
      READ 1,WL,BK,ZZ,BO,B1,B2
      READ 1,B3,BS,HO,HX,HY,HZ
      READ 1,HS,HT,HW,QQ,W,RF
      READ 1,SC,YY,C,TS,SN,DB
      READ 1,CE,SH,SD,TT,SK,T1
      READ 1,RS,GC,GP,C1,CW,CP
      READ 1,EL,CM,CQ,BP,PL,HP
      READ 1,PE,DR,RK,CC,WR,D1
      READ 1,WO,HD,DD,H,B,BN
      READ 1,SB,TB,RE,T3,DSH,DISH
      READ 1,ALH,TYPY,PCOIL,DCOIL,BCOIL,TY
      READ 1,TYE,TYR,DYC,PT,FE,RD
      READ 1,RT,T2,RR,SNL,WF,CS
      READ 1,AS,FS,TP,DF,CF,EC
      READ 1,AC,S,HP1,DISH1,PM,P5
      READ1,P6,P7,PBA
      GA=3.142*DI*CL
      AG=6.38*DI/(PX*GC*CC)
      GE=CC*GC
      IF(C1) 44,43,44
   43 C1=(0.649*LOG(PE)+1.359)*((GC/GP)**0.352)
   44 IF(CW)45,45,46
   45 CW=0.707*EE*C1*DF/(EP*PN)
```

```
46 TG=6000000.0*EE/(CW*EC*RPM)
   BG=TG/GA
   IF(CP)47,47,48
47 CP=(GC/GP)**0.41*PE*(LOG(GC/TP)*.0378+1.191)
48 FQ=TG*CP/PX
   IF(ZZ-3.0)49,50,51
49 SM=TT-BS
   GO TO 53
50 SM=(3.1416*(DI+2.*HS)/QQ)-B3
   GO TO 53
51 IF(ZZ-4.0)50,52,49
52 SM=TT-.94*BS
53 IF(EL) 54,54,62
54 IF(RF) 55,55,61
55 IF(PX-2.0) 56,56,57
56 U=1.3
   GO TO 60
57 IF(PX-4.0) 58,58,59
58 U=1.5
   GO TO 60
59 U=1.7
60 EL=3.142*U*YY*(DI+HS)/QQ+0.5
   GO TO 62
61 EL=2.0*CE+(3.142*(0.5*HX+DB))+(YY*TS*TS/(SQRT(TS*TS-BS*BS)))
62 HM=CL+EL
   RX=RS*0.000001
   RB=(T1+234.5)*0.00394*RX
   IF(SH)37,38,40
38 ET=1
```

```
      EB=1
      GO TO 39
   40 AA=0.584+(SN*SN-1.0)*0.0625*(SD*CL/(SH*HM))*2.0
      AB=(SH*SC*F*AG/(BS*RB*1000000.0))**2.0
      ET=AA*AB*0.00335+1.0
      EB=ET-0.00168*AB
   39 IF(CM)63,63,64
   63 AA=SIN(3.142*PE)
      AB=SIN(1.571*PE)*4.0
      CM=(3.142*PE+AA)/AB
   64 PRINT3,SS,CC,HC,GA,TS,AG,TT,GE,FS,C1,DF,CW,CF,CP,EC,EL,AC,CM
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,CK,POL,DI
      PUNCH1,DU,CL,SS,HC,SF,QN
      PUNCH1,WL,BK,ZZ,B0,B1,B2
      PUNCH1,B3,BS,H0,HX,HY,HZ
      PUNCH1,HS,HT,HW,QQ,W,GE
      PUNCH1,SC,YY,C,TS,BG,TG
      PUNCH1,FQ,TT,HM,SM,GA,EC
      PUNCH1,GC,C1,CW,CP,RX,RB
      PUNCH1,EL,CM,CQ,BP,HP,HP1
      PUNCH1,PL,PE,DR,RK,CC,WR
      PUNCH1,D1,WO,HD,DD,H,B
      PUNCH1,BN,SB,TB,RE,T3,DSH
      PUNCH1,DISH,ALH,TYPY,PCOIL,DCOIL,BCOIL
      PUNCH1,TY,TYE,TYR,DYC,PT,FE
      PUNCH1,RD,RT,T2,RR,SNL,WF
      PUNCH1,CS,AS,ET,TP,DF,CF
      PUNCH1,EB,AC,S,AG,SM,DISH1
```

```
PUNCH1,PM,P5,P6,PM,PBA
PAUSE
END
```

```
C      PASS 3 HOMOPOLAR INDUCTOR
     1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
     3 FORMAT(9X F12.5,2X F12.5)
       READ1, VA,EE,EP,PN,F,PX
       READ1, RPM,PI,PF,CK,POL,DI
       READ1, DU,CL,SS,HC,SF,QN
       READ1, WL,BK,ZZ,BO,B1,B2
       READ1, B3,BS,HO,HX,HY,HZ
       READ1, HS,HT,HW,QQ,W,GE
       READ1, SC,YY,C,TS,BG,TG
       READ1 ,FQ,TT,HM,SM,GA,EC
       READ 1,GC,C1,CW,CP,RX,RB
       READ 1,EL,CM,CQ,BP,HP,HP1
       READ 1,PL,PE,DR,RK,CC,WR
       READ 1,D1,WO,HD,DD,H,B
       READ 1,BN,SB,TB,RE,T3,DSH
       READ 1,DISH,ALH,TYPY,PCOIL,DCOIL,BCOIL
       READ 1,TY,TYE,TYR,DYC,PT,FE
       READ 1,RD,RT,T2,RR,SNL,WF
       READ 1,CS,AS,ET,TP,DF,CF
       READ 1,EB,AC,S,AG,SM,DISH1
       READ1,PM,P5,P6,P7,PBA
       FGML=.45*EC*PI*CM*DF/PX
       A=PI*SC*CF/(C*TS)
       RY=SC*QQ*HM/(PN*AC*C*C)
       RG=RX*RY*2.
       RP=RB*RY*2.
       IF(CQ)69,69,70
    69 AA=1.571*PE
```

```
      AB=3.1416*PE
      CQ=(0.5*COS(AA)+AB-SIN(AB))/(4.0*SIN(AA))
   70 XR=.0707*A*DF/(C1*BG)
      ZX=YY/(PN*QN)
      IF(ZZ-5.)350,351,350
  351 FF=1.0
      GO TO 75
  350 IF(PBA-60.)352,353,352
  353 IF(ZX-.667)354,355,355
  355 D=.75
      Z=.25
      GO TO 74
  354 D=1.5
      Z=-.25
      GO TO 74
  352 IF(ZX-.667)356,357,357
  357 FF=.75
      GO TO 75
  356 D=1.2
      Z=-.05
   74 FF=D*ZX+Z
   75 CX=FF/(CF*CF*DF*DF)
      Z=CX*20.0/(PN*QN)
      BT=3.142*DI/QQ-BO
      ZA=BT*BT/(16.0*TS*GC)
      ZB=0.35*BT/TS
      ZC=HO/BO
      ZD=HX*0.333/BS
      ZE=HY/BS
```

```
      IF(ZZ-2.0) 76,77,78
76    PC=Z*(ZE+ZD+ZA+ZB)
      GO TO 82
77    PC=Z*(ZC+(2.0*HT/(BO+BS))+(HW/BS)+ZD+ZA+ZB)
      GO TO 82
78    IF(ZZ-4.0) 79,80,81
79    PC=Z*(ZC+(2.0*HT/(BO+B1))+(2.0*HW/(B1+B2))+(HX*0.333/B2)+ZA+ZB)
      GO TO 82
80    PC=Z*(ZC+0.62)
      GO TO 82
81    PC=Z*(ZE+ZD+(0.5*GC/TS)+(0.25*TS/GC)+0.6)
82    WC=.642*SC*QQ*AC*HM
      ZA=3.1416*(DI+HS)/QQ
      IF(ZZ-3.0) 88,89,88
88    TM=ZA-BS
      GO TO 86
89    TM=(3.1416*(DI+2.*HS)/QQ)-B3
86    WI=(TM*QQ*SS*HS+(DU-HC)*3.142*HC*SS)*.566
      AN=0.0
100   AN=AN+0.005
      AL=COS(AN)
      IF(PF-AL) 100,100,101
101   VR=0.262*DR*RPM
      AP=BP*PL*RK
      FH=BG*GE/0.00319
      ZG=PT*FE*0.000001/AS
      FK=RR*ZG
      FR=(T2+234.5)*FK*0.00394
      RC=.321*PT*FE*AS
```

```
PRINT3,S,CQ,HM,A,RG,XR
PUNCH1,VA,EE,EP,PN,F,PX
PUNCH1,RPM,PI,PF,CK,POL,DI
PUNCH1,DU,CL,SS,HC,PC,QN
PUNCH1,WL,BK,ZZ,BO,PE
PUNCH1,XR,BS,CQ,HX,HY,HZ
PUNCH1,HS,WC,AC,QQ,W,GE
PUNCH1,SC,YY,C,TS,BG,TG
PUNCH1,FQ,TT,EL,AG,GA,FGML
PUNCH1,RG,GC,RP,C1,TP,CP
PUNCH1,DF,CM,CF,BP,HP,HP1
PUNCH1,PL,EB,DR,RK,CC,WR
PUNCH1,D1,WO,HD,DD,H,B
PUNCH1,BN,SB,TB,RE,T3,DSH
PUNCH1,DISH,ALH,TYPY,PCOIL,DCOIL,BCOIL
PUNCH1,TY,TYE,TYR,DYC,PT,FE
PUNCH1,RD,RT,T2,RR,SNL,WF
PUNCH1,CS,AS,ET,SM,HO,HT
PUNCH1,B1,B3,SM,DISH1,PM,P5
PUNCH1,TM,WI,AN,VR,AP,FH
PUNCH1,FK,FR,RC,AL,P6,P7
PAUSE
END
```

```
C       PASS 4 HOMOPOLAR INDUCTOR
      1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      3 FORMAT(9X F12.5,2X F12.5)
        READ1, VA,EE,EP,PN,F,PX
        READ1, RPM,PI,PF,CK,POL,DI
        READ1, DU,CL,SS,HC,PC,QN
        READ 1,WL,BK,ZZ,BO,PE
        READ 1,XR,BS,CQ,HX,HY,HZ
        READ1, HS,WC,AC,QQ,W,GE
        READ1, SC,YY,C,TS,BG,TG
        READ 1,FQ,TT,EL,AG,GA,FGML
        READ1, RG,GC,RP,C1,TP,CP
        READ 1,DF,CM,CF,BP,HP,HP1
        READ 1,PL,EB,DR,RK,CC,WR
        READ 1,D1,WO,HD,DD,H,B
        READ 1,BN,SB,TB,RE,T3,DSH
        READ 1,DISH,ALH,TYPY,PCOIL,DCOIL,BCOIL
        READ 1,TY,TYE,TYR,DYC,PT,FE
        READ 1,RD,RT,T2,RR,SNL,WF
        READ 1,CS,AS,ET,SM,HO,HT
        READ 1,B1,B3,SM,DISH1,PM,P5
        READ 1,TM,WI,AN,VR,AP,FH
        READ 1,FK,FR,RC,AL,P6,P7
        EK=EL/(10.0**(0.103*YY*TS+0.402))
        IF(DI-8.0) 83,83,84
     83 EK=SQRT(EK)
     84 ZF=.612*LOG(10.0*CS)
        EW=6.28*EK*ZF*(TP**(0.62-(0.228*LOG(ZF))))/(CL*DF*DF)
        XL=(PC+EW)*XR*2.
```

```
      XD=XR*AG*C1*CM
      XQ=XR*CQ*AG
      IF(PM)341,340,341
  340 PM=10.02*DR*CL/(PX*(HP1+GC))
  341 IF(P5)343,342,343
  342 P5=1.675*(DCOIL-PCOIL)*(DCOIL+PCOIL)/BCOIL
  343 IF(P6)345,344,345
  344 P6=2.5*(PCOIL-DI)*(PCOIL+DI)/BCOIL
  345 IF(P7)347,346,347
  346 P7=2.5*(DI+DISH1)*(DU-DI)/(DU-DISH1)
  347 RL=(P5+P6+PM*PX/4.)/CL
      XF=(1.0-C1/((1.273*RL/AG+2.0*CP)*CM))*XD
      SI=PT*PT*(PX*.3927*CP*AG*PL+RL)*1.E-8
      IF(BN)307,306,307
  306 X1=0
      P2=0
      X2=0
      GO TO 308
  307 IF(DD)103,103,102
  102 ZG=0.62
      GO TO 104
  103 ZG=0.333*H/B
  104 ZF=HD/WO+ZG+.5
      BD=ZF*6.38
      BE=(BH-(BP-1.0)*TB)*2.127/GE
      P1=(BD+BE)*RL*COS((BN-1.0)*TB*1.572/TP)/(BD+BE+RL)
      X1=XR*P1
      P2=(ZF+GC/TB)*20.0*TB/TP
      X2=XR*P2
```

```
308 XA=XL+XD
    XB=XL+XQ
    XU=XL+XF
    XS=0.88*XU
    PRINT3,RP,XL,ET,XD,EB,XQ
    PRINT3,PC,XA,EW,XB,WC,XF,WI,SI,PM,X1,P5,X2,P6,XU,P7,XS
    PUNCH1,VA,EE,EP,PN,F,PX
    PUNCH1,RPM,PI,PF,CK,POL,DI
    PUNCH1,DU,CL,SS,HC,PC,QN
    PUNCH1,WL,BK,ZZ,BO,XD,XQ
    PUNCH1,XR,BS,PE,HX,HY,HZ
    PUNCH1,HS,AC,QQ,W,GE
    PUNCH1,SC,YY,C,TS,BG,TG
    PUNCH1,FQ,TT,EW,AG,GA,FGML
    PUNCH1,RG,GC,RP,C1,AP,P2
    PUNCH1,DF,WF,CF,FH,BP,PM
    PUNCH1,P5,P6,P7,HP,HP1
    PUNCH1,PL,EB,DR,RK,CC,WR
    PUNCH1,D1,WO,SI,DD,H,B
    PUNCH1,BN,SB,TB,RE,T3,DSH
    PUNCH1,DISH,ALH,TYPY,PCOIL,DCOIL,BCOIL
    PUNCH1,TY,TYE,TYR,DYC,PT,VR
    PUNCH1,RD,RT,SNL,CS,AS,ET
    PUNCH1,FK,FR,XA,XB,AN,AL
    PUNCH1,RC,HD,XS,XL,X1,X2
    PUNCH1,SM,DISH1,TP
    PAUSE
    END
```

```
C     PASS 5 HOMOPOLAR INDUCTOR
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    3 FORMAT(9X F12.5,2X F12.5)
      READ1, VA,EE,EP,PN,F,PX
      READ1, RPM,PI,PF,CK,POL,DI
      READ1, DU,CL,SS,HC,PC,QN
      READ1, WL,BK,ZZ,BO,XD,XQ
      READ 1,XR,BS,PE,HX,HY,HZ
      READ 1,HS,AC,QQ,W,GE
      READ1, SC,YY,C,TS,BG,TG
      READ 1,FQ,TT,EW,AG,GA,FGML
      READ1, RG,GC,RP,C1,AP,P2
      READ 1,DF,WF,CF,FH,BP,PM
      READ 1,P5,P6,P7,HP,HP1
      READ 1,PL,EB,DR,RK,CC,WR
      READ 1,D1,WO,SI,DD,H,B
      READ 1,BN,SB,TB,RE,T3,DSH
      READ 1,DISH,ALH,TYPY,PCOIL,DCOIL,BCOIL
      READ 1,TY,TYE,TYR,DYC,PT,VR
      READ 1,RD,RT,SNL,CS,AS,ET
      READ 1,FK,FR,XA,XB,AN,AL
      READ 1,RC,HD,XS,XL,X1,X2
      READ 1,SM,DISH1,TP
      IF(BN)105,105,106
  105 XX=XS
      XY=XB
      GO TO 107
  106 XX=XL+X1
      XY=XL+X2
```

```
107 XN=(XX+XY)*0.5
    TC=SI/FK
    RA=PN*PI*PI*RP*0.001/VA
    TA=XN/(628.4*F*RA)
    T5=XS*TC/XA
    IF(F-60.0)108,108,109
108 T4=0.035
    GO TO 110
109 T4=0.005
110 IF(WF)111,111,112
111 WF=DR**2.5*(RPM**1.5)*PL*0.00000252
112 IF(ZZ-1.0)301,301,302
301 BO=BS
302 GT=BO/GC
    IF(GT-1.0)304,304,303
304 AA=2.6
    GO TO 115
303 IF(GT-3.75)113,114,114
113 AA=10.0**0.178/((GT-1.0)**0.334)
    GO TO 115
114 AA=10.0**0.11/((GT-1.0)**0.174)
115 GF=AA*PI*SC/(C*FH)
305 IF(SC-1.0)121,121,122
120 A5=0.0
    GO TO 129
121 AX=1.0
    AY=1.0
    GO TO 125
122 AX=3.0*YY/(PN*QN)-2.0
```

```
      IF(CS-0.667)123,124,124
  123 AY=1.5*YY/(PN*QN)-0.25
      GO TO 125
  124 AY=.75*YY/(PN*QN)+0.25
  125 A3=AX*P2/AY
      A4=0.07*AX*AG/(CF*CF)
      IF(AX)120,120,126
  126 IF(BN)127,127,128
  127 A5=A4
      GO TO 129
  128 A5=(A4+A3)/(A3*A4)
  129 IF(W)130,130,131
  130 XO=0.0
      GO TO 132
  131 AA=(3.0*HZ+HX)*1.667/(PN*QN*CF*CF*DF*DF*BS)
      XO=((PC+A5)*AX/AY+AA+0.2*EW)*XR
  132 AA=WO/(GC*CC)
      VT=0
      IF(AA)148,147,148
  148 IF(AA-0.65)145,147,146
  145 VT=LOG(10.0*AA)*(-0.242)+0.59
      GO TO 147
  146 VT=0.327-(AA*0.266)
  147 EZ=(ET+EB)*0.5-1.0
      AA=PN*PI*PI
      PU=AA*RG
      PV=AA*RP
      VV=EP*PI*PF*.003
      FSC=XA*FH*0.01*2
```

```
      ACR=(DU-2.*HC)*3.1416*PE*SS/PX
      ATH=QQ*SS*SM
      PRINT3,AS,XX,FK,XY,FR,XN,RC,XO,WR,TG,VR,FQ
      PRINT348,BG
  348 FORMAT(23X,F12.5)
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,CK,POL,TB
      PUNCH1,BO,GC,HP,HP1,PL,DR
      PUNCH1,SB,RE,T3,PT,T5,T4
      PUNCH1,WO,DD,H,BN,GF,VT
      PUNCH1,SNL,TS,CC,BG,FK,AP
      PUNCH1,FQ,FR,XD,FH,GA,HC
      PUNCH1,AN,AL,XA,WF,TC,TA
      PUNCH1,AS,HS,B,GE,BP,XB
      PUNCH1,EZ,PU,VV,FSC,PV,HD
      PUNCH1,QN,DSH,DISH,ALH,TYPY,PCOIL
      PUNCH1,DCOIL,BCOIL,TY,TYE,TYR,DYC
      PUNCH1,C1,DI,CL,QQ,GA,SM
      PUNCH1,DU,FGML,ATH,PM,ACR,P5
      PUNCH1,P6,P7,TT,SS,BK,WL
      PUNCH1,TG,DISH1,TP,D1
      PAUSE
      END
```

```
C     PASS 6 HOMOPOLAR INDUCTOR
      DIMENSION AI(90)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
  250 FORMAT(9X F12.5,2X F12.5/)
  888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
    3 FORMAT(9X F12.5,2X F12.5)
      K=1
  823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K-89)823,199,199
  199 READ 1,VA,EE,EP,PN,F,PX
      READ 1,RPM,PI,PF,CK,POL,TB
      READ 1,BO,GC,HP,HP1,PL,DR
      READ 1,SB,RE,T3,PT,T5,T4
      READ 1,WO,DD,H,BN,GF,VT
      READ 1,SNL,TS,CC,BG,FK,AP
      READ 1,FQ,FR,XD,FH,GA,HC
      READ 1,AN,AL,XA,WF,TC,TA
      READ 1,AS,HS,B,GE,BP,XB
      READ 1,EZ,PU,VV,FSC,PV,HD
      READ 1,QN,DSH,DISH,ALH,TYPY,PCOIL
      READ 1,DCOIL,BCOIL,TY,TYE,TYR,DYC
      READ 1,C1,DI,CL,QQ,GA,SM
      READ 1,DU,FGML,ATH,PM,ACR,P5
      READ 1,P6,P7,TT,SS,BK,WL
      READ 1,TG,DISH1,TP,D1
      PHM=PM*FH*.001
      FGM=FH+PX*PHM*GE/(.00319*GA)
      BP=(FQ+PHM)/AP
```

```
      X=BP
      NA=31
      K=1
      GO TO 802
  805 FP=HP*AT
      PH5=P5*(FGM+FH)*.001
      PH6=P6*(FGM+FH)*.001
      PH7=P7*FGM*.001
      PSH=(PX*FQ/2.)+PX*PHM+PH7
      BT=(TG+PHM*PX)/ATH
      X=BT
      NA=1
      K=2
      GO TO 802
  806 FT=HS*AT
      BC=(FQ+PHM)/ACR
      X=BC
      NA=1
      K=3
      GO TO 802
  807 FC=HC*AT
      ASH=(DSH**2-DISH**2)*.7854
      BSH=PSH/ASH
      NA=31
      K=4
      X=BSH
      GO TO 802
  808 FSH=ALH *AT
      AY=TY*(DU+TY)*3.1416
```

```
      IF(TYPY-2.)816,815,822
  822 ALY=1.334*CL
      GO TO 821
  816 AYR=0
      AYC=0
      ALY=BCOIL+.667*CL
      ALYR=0
      ALYC=0
      GO TO 817
  815 ALY=.667*CL
  821 AYC=DYC+TYE
      AYR=TYR*(DU+2.*TY)*3.1416
      ALYC=BCOIL
      ALYR=DYC-DU
  817 Z=PSH+PH5+PH6
      X=Z/AY
      BY=X
      NA=61
      K=5
      GO TO 802
  809 FY=ALY*AT
      IF(TYPY-1.)818,819,818
  818 X=Z/AYC
      BYC=X
      NA=61
      K=6
      GO TO 802
  810 FYC=ALYC*AT
      X=Z/AYR
```

```
      NA=61
      K=7
      GO TO 802
  811 FYR=ALYR*AT
  820 FNL=2.*(FGM+FT+FC+FP)+FSH+FY+FYC+FYR
      PRINT3,TC,BT,TA,BC,T5,FT,T4,FC
      PRINT250,FSC,FH
      PUNCH1,ATH,FT,FGML,PM,FNL,FH
      PUNCH1,GE,PX,GA,FQ,XA,PHM
      PUNCH1,AP,HP,D1,P5,P6,P7
      PUNCH1,ALH,BT,HS,ACR,HC,AY
      PUNCH1,ALY,AYC,ALYC,AYR,ALYR
      PUNCH1,PT,FK,FR,AS,VA,EE
      PUNCH1,PN,F,RPM,PI,PF,POL
      PUNCH1,BO,GC,DR,SB,RE,T3
      PUNCH1,WO,DD,H,BN,GF,VT
      PUNCH1,SNL,TS,CC,BG,WF,TB
      PUNCH1,B,BP,XB,EZ,PU,VV
      PUNCH1,FSC,PV,HD,QN,XD,EP
      PUNCH1,SM,DU,SS,QQ,BK,WL
      PUNCH1,TT,BC,BSH,ASH,TG,BYC
      PUNCH1,TP,AN,AL,TYPY,C1,FGM
      PUNCH1,CK
      PAUSE
  802 IF(AI(NA)-X)830,831,831
  831 NA=NA+3
  835 1F(AI(NA)-X)833,834,834
  833 NA=NA+2
      GO TO 835
```

```
834 AA=AI(NA)
    BB1=AI(NA-2)
    DC=AI(NA+1)
    D=AI(NA-1)
    XX=(AA-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
    Y=AA-XX*.4343*LOG(DC)
       AT=EXP(2.306*(X-Y)/XX)
    GO TO (805,806,807,808,809,810,811),K
830 PRINT850
850 FORMAT(17HMACHINE SATURATED)
    PAUSE
819 FYC=0
    FYR=0
    BYC=BY
    GO TO 820
    END
```

```
C     PASS 6A HOMOPOLAR INDUCTOR
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      READ 1,ATH,FT,FGML,PM,FNL,FH
      READ 1,GE,PX,GA,FQ,XA,PHM
      READ 1,AP,HP,D1,P5,P6,P7
      READ 1,ALH,BT,HS,ACR,HC,AY
      READ 1,ALY,AYC,ALYC,AYR,ALYR
      READ 1,PT,FK,FR,AS,VA,EE
      READ 1,PN,F,RPM,PI,PF,POL
      READ 1,BO,GC,DR,SB,RE,T3
      READ 1,WO,DD,H,BN,GF,VT
      READ 1,SNL,TS,CC,BG,WF,TB
      READ 1,B,BP,XB,EZ,PU,VV
      READ 1,FSC,PV,HD,QN,XD,EP
      READ 1,SM,DU,SS,QQ,BK,WL
      READ 1,TT,BC,BSH,ASH,TG,BYC
      READ 1,TP,AN,AL,TYPY,C1,FGM
      READ 1,CK
      IF(RE)309,309,311
  309 WD=0.0
      WU=0.0
      GO TO 178
  311 FS1=2.0*QN*PN*F
      FS2=2.0*FS1
      M=0
  150 IF(M-1)151,152,178
  151 RM=RE
      GO TO 153
  152 RM=RE*(T3+234.5)/254.5
```

```
153 AA=(FS1/RM)**0.5*DD*0.32
    AB=(FS2/RM)**0.5*DD*0.32
    IF(AA-2.5) 160,160,161
160 V1=1.0-0.15*AA+0.3*AA*AA
    GO TO 162
161 V1=AA
162 IF(AB-2.5) 163,163,164
163 V2=1.0-0.15*AB+0.3*AB*AB
    GO TO 165
164 V2=AB
165 IF(H-B) 167,166,167
166 VC=0.75/V1
    GO TO 169
167 IF(DD) 166,168,166
168 VC=H/(3.0*B*V1)
169 VS=HD/WO+VT+VC
    VG=TB/(CC*GC)
    Q1=1.0-(1.0/(((BO*0.5/GC)**2.0+1.0)**0.5))
    QZ=BO/TS
    Q2=1.05*SIN(QZ*2.844)
    IF(QZ-0.37)170,170,171
170 Q3=0.46
    GO TO 172
171 Q3=0.23*SIN(10.46*QZ-2.1)+0.23
172 Q4=SIN(6.283*TB/TS-1.571)+1.0
    Q5=SIN(12.566*TB/TS-1.571)+1.0
    IF(H)173,173,174
173 AB=0.785*DD*DD
    GO TO 175
```

```
174 AB=H*DD
175 W2=PX*BN*SB*RM*1.246/(AB*1000.)
    W3=(Q2/(2.0*VS+(VG/Q4)))**2.0*V1
    W5=(Q3/(2.0*VS+(VG/Q5)))**2.0*V2
    WD=(TS*BG*Q1*CC)**2.0*W2*(W3+W5)
    M=M+1
    IF(M-1)176,176,177
176 WU=WD
177 GO TO 150
178 PUNCH1,ATH,FT,FGML,PM,FNL,FH
    PUNCH1,GE,PX,GA,FQ,XA,PHM
    PUNCH1,AP,HP,P5,P6,P7
    PUNCH1,ALH,BT,HS,ACR,HC,AY
    PUNCH1,ALY,AYC,ALYC,AYR,ALYR
    PUNCH1,PT,FK,FR,AS,VA,EE
    PUNCH1,PN,F,RPM,PI,PF,POL
    PUNCH1,BO,GC,DR,SB,RE,T3
    PUNCH1,WO,DD,H,BN,GF,VT
    PUNCH1,SNL,TS,CC,BG,WF,TB
    PUNCH1,B,BP,XB,EZ,PU,VV
    PUNCH1,FSC,PV,HD,QN,XD,EP
    PUNCH1,SM,DU,SS,QQ,BK,WL
    PUNCH1,TT,BC,BSH,ASH,TG,BYC
    PUNCH1,TP,AN,AL,TYPY,WU,WD
    PUNCH1,C1,FGM,D1,CK
    PAUSE
    END
```

```
C     PASS 7 HOMOPOLAR INDUCTOR
      DIMENSION GX(4),YA(4),ED(4),FGX(4)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      READ 1,ATH,FT,FGML,PM,FNL,FH
      READ 1,GE,PX,GA,FQ,XA,PHM
      READ 1,AP,HP,P5,P6,P7
      READ 1,ALH,BT,HS,ACR,HC,AY
      READ 1,ALY,AYC,ALYC,AYR,ALYR
      READ 1,PT,FK,FR,AS,VA,EE
      READ 1,PN,F,RPM,PI,PF,POL
      READ 1,BO,GC,DR,SB,RE,T3
      READ 1,WO,DD,H,BN,GF,VT
      READ 1,SNL,TS,CC,BG,WF,TB
      READ 1,B,BP,XB,EZ,PU,VV
      READ 1,FSC,PV,HD,QN,XD,EP
      READ 1,SM,DU,SS,QQ,BK,WL
      READ 1,TT,BC,BSH,ASH,TG,BYC
      READ 1,TP,AN,AL,TYPY,WU,WD
      READ 1,C1,FGM,D1,CK
      D2=BG**2.5*0.000061
      D3=(0.0167*QQ*RPM)**1.65*0.000015147
      IF(TS-0.9) 133,133,134
  133 D4=TS**1.285*0.81
      GO TO 137
  134 IF(TS-2.0) 135,135,136
  135 D4=TS**1.145*0.79
      GO TO 137
  136 D4=TS**0.79*0.92
  137 D7=BO/GC
```

```
      IF(D7-1.7) 138,138,139
  138 D5=D7**2.31*0.3
      GO TO 144
  139 IF(D7-3.0) 140,140,141
  140 D5=D7**2.0*0.35
      GO TO 144
  141 IF(D7-5.0) 142,142,143
  142 D5=D7**1.4*0.625
      GO TO 144
  143 D5=D7**0.965*1.38
  144 D6=10.0**(0.932*C1-1.606)
      WN=D1*D2*D3*D4*D5*D6*GA
      WT=(SM)*QQ*SS*HS*0.453*(BT/BK)**2.0*WL
      WQ=(DU-HC)*1.42*HC*SS*(BC/BK)**2.0*WL
      YA(1)=100.
      YA(2)=66.66667
      YA(3)=50.
      IF(POL)310,320,310
  320 ED(4)=0
      GX(4)=0
      FGX(4)=0
      JA=3
      GO TO 330
  310 YA(4)=100./POL
      JA=4
  330 DO 99 K=1,JA
      AA=ATAN((XB/YA(K)+SIN(AN))/AL)
      BB=AA-AN
      ED(K)=XA*SIN(AA)/YA(K)+COS(BB)
```

```
      FGX(K)=FGML*100./YA(K)
      IF(PF-.95)213,213,212
  212 GX(K)=FQ*CK
      GO TO 99
  213 GX(K)=(ED(K)-(.93*XD*SIN(AA)/YA(K)))*FQ
   99 CONTINUE
      IF(POL)820,821,820
  820 AJ=4
      GO TO822
  821 AJ=3
  822 PUNCH1,ED(1),ED(2),ED(3),ED(4),AJ,BC
      PUNCH1,GX(1),GX(2),GX(3),GX(4),FGM
      PUNCH1,FGX(1),FGX(2),FGX(3),FGX(4)
      PUNCH1,FT,PF,PM,FH,PX
      PUNCH1,GE,AP,HP,P5,P6
      PUNCH1,P7,PHM,ASH,ALH,BT,ATH
      PUNCH1,HS,HC,ACR,TYPY,AY,AYC
      PUNCH1,AYR,ALY,ALYC,ALYR,BP,BSH
      PUNCH1,BYC,FNL,TG,GA,FQ,TP
      PUNCH1,POL,PU,FK,PV,FR,WU
      PUNCH1,WD,PT,AS,WF,WQ,GF
      PUNCH1,WT,XA,VV,WN,EZ,SNL
      PUNCH1,FH,PX,GE,AP,HP
      PUNCH1,P5,P6,P7,ASH,ALH,ATH
      PUNCH1,HS,HC,ACR,TYPY,AY,AYC
      PUNCH1,AYR,ALY,ALYC,ALYR,BC,BT
      PUNCH1,TG,GA,FQ,TP,EP,PM
      PAUSE
      END
```

```
C     PASS 8 HOMOPOLAR INDUCTOR
    4 FORMAT (F11.3,8X F11.3,F11.3,F11.3,F11.3)
  888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
      DIMENSION FFL(5),BSHLL(4),BCL(4),BTL(4),BPLL(4),BYCL(4),FGLL(4)
      DIMENSION GX(4),ED(4),PMLL(4),AI(90),FGX(4)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      K=1
  823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K-89)823,199,199
  199 READ 1,ED(1),ED(2),ED(3),ED(4),AJ,BC
      READ 1,GX(1),GX(2),GX(3),GX(4),FGM
      READ1 ,FGX(1),FGX(2),FGX(3),FGX(4)
      READ 1,FT,PF,PM,FH,PX
      READ1 ,GE,AP,HP,P5,P6
      READ 1,P7,PHM,ASH,ALH,BT,ATH
      READ 1,HS,HC,ACR,TYPY,AY,AYC
      READ1,AYR, ALY,ALYC,ALYR,BP,BSH
      READ1,BYC,FNL,TG,GA,FQ,TP
      DO 886 J=1,4
      PMLL(J)=0
      FFL(J+1)=0
      BSHLL(J)=0
      BCL(J)=0
      BTL(J)=0
      BPLL(J)=0
      BYCL(J)=0
  886 FGLL(J)=0
      JA=AJ
```

```
      DO 885 J=1,JA
      PPL=GX(J)
      EDD=ED(J)
      FGML=FGX(J)
      FTL=FT*(1.+PF)
      PML=PM*(FGML+FH*EDD)*.001
      ZZ=PX*GE/(.00319*GA)
      FGL=FH*EDD+PML*ZZ
      BPL=(PPL+PML)/AP
      NA=31
      K=1
      X=BPL
      GO TO 802
  870 FPL=AT*HP
      Z=FGL+FTL+FPL
      PH5L=P5*.002*Z
      PH6L=P6*.002*Z
      PH7L=P7*.001*Z
      PSHL=(PPL*PX/2.)+PX*PML+PH7L
      BSHL=PSHL/ASH
      X=BSHL
      NA=31
      K=2
      GO TO 802
  871 FSHL=ALH*AT
      PML=PM*(FGML+FGL)*.001
      PMLL(J)=PML
      PPLL=PPL+PML
      X=PPLL/AP
```

```
      BPLL(J)=X
      NA=31
      K=3
      GO TO 802
  872 FPL=AT*HP
      FGL=FH*EDD+PML*ZZ
      FGLL(J)=FGL
      X=(TG+PX*PML)/ATH
      BTL(J)=X
      NA=1
      K=4
      GO TO 802
  873 FTL=AT*HS
      Z=FTL+FGL+FPL
      PH7L=P7*Z*.001
      PSHL=(PPLL*PX/2.)+PX*PML/2.+PH7L
      X=PSHL/ASH
      NA=31
      K=5
      BSHLL(J)=X
      GO TO 802
  874 FSHL=ALH*AT
      Z=2.*Z+FSHL
      PH5L=P5*Z*.001
      PH6L=P6*Z*.001
      PCL=PPLL+(PH5L+PH6L)/PX
      X=PCL/ACR
      BCL(J)=X
      NA=1
```

```
      K=6
      GO TO 802
  875 FCL=AT*HC
      IF(TYPY-1.)880,881,880
  881 PY=PSHL+PH6L+PH5L
      GO TO 882
  880 PY=PSHL+PH6L
  882 X=PY/AY
      NA=61
      K=7
      GO TO 802
  876 FYL=AT*ALY
      IF(TYPY-1.)883,884,883
  883 PY=PSHL+PH6L+PH5L
      X=PY/AYC
      BYCL(J)=X
      NA=61
      K=8
      GO TO 802
  877 FYCL=AT*ALYC
      X=PY/AYR
      NA=61
      K=9
      GO TO 802
  878 FYRL=AT*ALYR
  889 FFL(J+1)=2.*(FGL+FTL+FCL+FPL)+FSHL+FYL+FYCL+FYRL
  885 CONTINUE
      PRINT4,PHM,PMLL(1),PMLL(2),PMLL(3),PMLL(4)
      PRINT4,FGM,FGLL(1),FGLL(2),FGLL(3),FGLL(4)
```

```
      PRINT4,BP,BPLL(1),BPLL(2),BPLL(3),BPLL(4)
      PRINT4,BT,BTL(1),BTL(2),BTL(3),BTL(4)
      PUNCH1,BT,BTL(1),BTL(2),BTL(3),BTL(4)
      PRINT4,BSH,BSHLL(1),BSHLL(2),BSHLL(3),BSHLL(4)
      PRINT4,BC,BCL(1),BCL(2),BCL(3),BCL(4)
      PUNCH1,BC,BCL(1),BCL(2),BCL(3),BCL(4)
      PRINT4,BYC,BYCL(1),BYCL(2),BYCL(3),BYCL(4)
      PUNCH1,FNL,FFL(2),FFL(3),FFL(4),FFL(5)
      DO 887 K=1,8
      READ 1,R1,R2,R3,R4,R5,R6
  887 PUNCH1,R1,R2,R3,R4,R5,R6
      PAUSE
  884 FYCL=0
      FYRL=0
      BYCL(J)=X
      GO TO 889
  802 IF(AI(NA)-X)830,831,831
  831 NA=NA+3
  835 IF(AI(NA)-X)833,834,834
  833 NA=NA+2
      GO TO 835
  834 AA=AI(NA)
      BB1=AI(NA-2)
      DC=AI(NA+1)
      D=AI(NA-1)
      XX=(AA-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
      Y=AA-XX*.4343*LOG(DC)
         AT=EXP(2.306*(X-Y)/XX)
      GO TO (870,871,872,873,874,875,876,877,878),K
```

```
830 GO TO 885
    PAUSE
    END
```

```
C     PASS 9 HOMOPOLAR INDUCTOR
      DIMENSION PR(5),FI(5),PS(5),G(5),DL(5),PP(5),EX(5),ST(5),VA(5)
      DIMENSION P(5),E(5),PZ(5),SP(5),FFL(5),CDD(5),EF(5)
      DIMENSION BTL(5),BCL(5),WQL(5)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    4 FORMAT (F11.3,8X F11.3,F11.3,F11.3,F11.3)
      READ1,BT,BTL(2),BTL(3),BTL(4),BTL(5)
      READ1,BC,BCL(2),BCL(3),BCL(4),BCL(5)
      READ1,FNL,FFL(2),FFL(3),FFL(4),FFL(5)
      READ 1,POL,PU,FK,PV,FR,WU
      READ 1,WD,PT,AS,WF,WQ,GF
      READ 1,WT,XA,VV,WN,EZ,SNL
      READ 1,FH,PX,GE,AP,HP
      READ 1,P5,P6,P7,ASH,ALH,ATH
      READ 1,HS,HC,ACR,TYPY,AY,AYC
      READ 1,AYR,ALY,ALYC,ALYR,BC,BT
      READ 1,TG,GA,FQ,TP,EP,PM
      PRINT4,FNL,FFL(2),FFL(3),FFL(4),FFL(5)
      FFL(1)=FNL
      BTL(1)=BT
      BCL(1)=BC
      G(1)=0
      G(2)=1
      G(3)=1.5
      G(4)=2.
      G(5)=POL
      PW=PU
      FW=FK
      WW=WU
```

```
      DO 183 M=1,5
      FI(M)=FFL(M)/PT
      EF(M)=FI(M)*FW
      CDD(M)=FI(M)/AS
      UA=G(M)
      PR(M)=FI(M)*FI(M)*FW
      IF(FI(M))198,197,198
  198 PS(M)=PW*UA*UA
      WQL(M)=WQ*(BCL(M)/BC)**2
      X=WF+WQL(M)
      GM   =(GF*UA)**2.0+1.0
      ST(M)=(2.0*(0.0027*XA*UA)**1.8+1.0)*WT*(BTL(M)/BT)**2
      VA(M)=VV*UA
  181 DL(M)=GM   *WW
      PP(M)=GM   *WN
      EX(M)=EZ*PS(M)
      SP(M)=PP(M)+DL(M)+PR(M)+PS(M)+EX(M)+ST(M)+X
      P(M)=(SP(M)/1000.)+VA(M)
      IF(GM)185,184,185
  184 PZ(M)=0
      E(M)=0
      GO TO 186
  185 PZ(M)=(SP(M)/P(M))*.1
      E(M)=100.0-PZ(M)
  186 FW=FR
      WW=WD
  183 PW=PV
      PRINT4,FI(1),FI(2),FI(3),FI(4),FI(5)
      PRINT4,EF(1),EF(2),EF(3),EF(4),EF(5)
```

```
      PRINT4,CDD(1),CDD(2),CDD(3),CDD(4),CDD(5)
      PRINT4, PR(1),PR(2),PR(3),PR(4),PR(5)
      PRINT4, WF,WF,WF,WF,WF
      PRINT4, ST(1),ST(2),ST(3),ST(4),ST(5)
      PRINT4,WQL(1),WQL(2),WQL(3),WQL(4),WQL(5)
      PRINT4, PP(1),PP(2),PP(3),PP(4),PP(5)
      PRINT4, DL(1),DL(2),DL(3),DL(4),DL(5)
      PRINT4, PS(1),PS(2),PS(3),PS(4),PS(5)
      PRINT4, EX(1),EX(2),EX(3),EX(4),EX(5)
      PRINT4, SP(1),SP(2),SP(3),SP(4),SP(5)
      PRINT4, VA(1),VA(2),VA(3),VA(4),VA(5)
      PRINT4, E(1),E(2),E(3),E(4),E(5)
      IF(SNL)191,191,190
  190 PUNCH1,FH,PX,GE,AP,HP
      PUNCH1,P5,P6,P7,ASH,ALH,ATH
      PUNCH1,HS,HC,ACR,TYPY,AY,AYC
      PUNCH1,AYR,ALY,ALYC,ALYR,BC,BT
      PUNCH1,TG,GA,FQ,TP,EP,PM
  191 PAUSE
  197 PS(M)=0
      GM=0
      ST(M)=0
      WQL(M)=0
      X=0
      VA(M)=0
      GO TO 181
      END
```

```
C     PASS 10 HOMOPOLAR INDUCTOR
      DIMENSION AI(90)
  245 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
  246 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5//)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
  888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
      K=1
  823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K-89)823,199,199
  199 READ 1,FH,PX,GE,AP,HP
      READ 1,P5,P6,P7,ASH,ALH,ATH
      READ 1,HS,HC,ACR,TYPY,AY,AYC
      READ 1,AYR,ALY,ALYC,ALYR,BC,BT
      READ 1,TG,GA,FQ,TP,EP,PM
      R=.7
      FF=TG
      FG=FH
      DO 247 L=1,9
      R=R+.1
      TG=FF*R
      FH=FG*R
      V=1.732*EP*R
      PHM=PM*FH*.001
      FGM=FH+PX*PHM*GE/(.00319*GA)
      BP=(FQ+PHM)/AP
      X=BP
      NA=31
      K=1
```

```
      GO TO 802
  805 FP=HP*AT
      PH5=P5*(FGM+FH)*.001
      PH6=P6*(FGM+FH)*.001
      PH7=P7*FGM*.001
      PSH=(PX*FQ/2.)+PX*PHM+PH7
      BT=(TG+PHM*PX)/ATH
      X=BT
      NA=1
      K=2
      GO TO 802
  806 FT=HS*AT
      BC=(FQ+PHM)/ACR
      X=BC
      NA=1
      K=3
      GO TO 802
  807 FC=HC*AT
      BSH=PSH/ASH
      NA=31
      K=4
      X=BSH
      GO TO 802
  808 FSH=ALH *AT
  817 Z=PSH+PH5+PH6
      X=Z/AY
      BY=X
      NA=61
      K=5
```

```
      GO TO 802
809   FY=ALY*AT
      IF(TYPY-1.)818,819,818
818   X=Z/AYC
      BYC=X
      NA=61
      K=6
      GO TO 802
810   FYC=ALYC*AT
      X=Z/AYR
      NA=61
      K=7
      GO TO 802
811   FYR=ALYR*AT
820   FNL=2.*(FGM+FT+FC+FP)+FSH+FY+FYC+FYR
      PRINT245,V,FGM,BC,FC,BT,FT
247   PRINT246,BP,FP,BSH,FSH,BYC,FNL
      PAUSE
802   IF(AI(NA)-X)830,831,831
831   NA=NA+3
835   IF(AI(NA)-X)833,834,834
833   NA=NA+2
      GO TO 835
834   AA=AI(NA)
      BB1=AI(NA-2)
      DC=AI(NA+1)
      D=AI(NA-1)
      XX=(AA-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
      Y=AA-XX*.4343*LOG(DC)
```

```
      AT=EXP(2.306*(X-Y)/XX)
    GO TO (805,806,807,808,809,810,811),K
830 PRINT850
850 FORMAT(17HMACHINE SATURATED)
    PAUSE
819 FYC=0
    FYR=0
    BYC=BY
    GO TO 820
    END
```

PERMANENT-MAGNET A-C GENERATOR COMPUTER PROGRAM AND TEST DATA

GENERATOR COMPUTER DESIGN (INPUT) 5-11-65

MODEL NO. EWO DESIGN NO. (1)

Group	No.	Symbol	Item	Value
PARAMETERS	(2)	KVA	GENERATOR KVA	1.05
	(3)	f	LINE VOLTS	115
	(4)	E_{ph}	PHASE VOLTS	66.5
	(5)	m	PHASES	3
	(5a)	f	FREQUENCY	400
	(6)	p	POLES	6
	(7)	RPM	RPM	8000
	(8)	I_{ph}	PHASE CURRENT	5
	(9)	PF	POWER FACTOR	1.0
STATOR STACK	(11)	d	STATOR I.D.	3.75
	(12)	D	STATOR O.D.	5.54
	(13)		GROSS CORE LENGTH	1.625
	(14)	n_v	NO. OF DUCTS	0
	(15)	b_v	WIDTH OF DUCT	0
	(16)	K_i	STACKING FACTOR (STATOR)	.92
	(19)	k	WATTS/LB.	15
	(20)	B	DENSITY	77.4
STATOR SLOT	(21)		TYPE OF SLOT	3
	(22)	b_o	SLOT OPENING	.090
	(22)	b_1	SLOT WIDTH TOP	.186
	(22)	b_2		.190
	(22)	b_3		.266
	(22)	b_s	SLOT WIDTH	.226
	(22)	h_o		.031
	(22)	h_1		0
	(22)	h_2		0
	(22)	h_3		0
	(22)	h_s	SLOT DEPTH	.51
	(22)	h_t		.050
	(22)	h_w		0
	(23)	Q	NO. OF SLOTS	36
STATOR WINDING	(28)		TYPE OF WDG.	1
	(29)		TYPE OF COIL	0
	(30)	n_s	CONDUCTORS/SLOT	18
	(31)	y	SLOTS SPANNED	5
	(32)	c	PARALLEL CIRCUITS	1
	(33)		STRAND DIA. OR WIDTH	.0508
	(34)	N_{st}	STRANDS/CONDUCTOR	1
	(34a)	N'_{st}	STRANDS/CONDUSTOR	1
	(39)		STATOR STRAND T'KNS	0
	(35)	d_b	DIA. OF PIN	.1
	(36)	e_2	COIL EXT. STR. PORT	.2
	(37)	h_{st}	UNINS. STRD. HT.	0
	(38)	h'_{st}	DIST. BTWN. C_L OF STD.	0
	(42a)		PHASE BELT/ANGLE	60
	(40)	sk	STATOR SLOT SKEW	0
	(50)	X_s °C	STATOR TEMP °C	75
	(51)	s	RES'TVY STA. COND. @ 20 ° C	.694
GAP	(59)	g min	MINIMUM AIR GAP	.017
	(59a)	g max	MAXIMUM AIR GAP	.020

Value	Item	No.	Symbol	Group
1.075	FUND/MAX OF FIELD FLUX	(71)	C_1	CONSTANTS
.419	WINDING CONSTANT	(72)	C_w	
.657	POLE CONST.	(73)	C_p	
0	END EXTENSION ONE TURN	(48)	LE	
.84	DEMAGNETIZATION FACTOR	(74)	C_m	
.61	CROSS MAGNETIZING FACTOR	(75)	C_q	
1.38	POLE HEAD WIDTH	(76)	b_h	ROTOR STACK
1.0	MAGNET WIDTH	(76)	b_p	
.182	POLE HEAD HEIGHT	(76)	h_h	
.812	MAGNET HEIGHT	(76)	h_f	
1.625	MAGNET LENGTH	(76)	p	
1.625	POLE HEAD LENGTH	(76)	n	
.71	POLE EMBRACE	(77)	α_c	
3.716	ROTOR DIAMETER	(11a)	d_r	
1.0	STACKING FACTOR(ROTOR)	(16)	K_i	
0	WEIGHT OF ROTOR IRON	(157)	(–)	
7.0	POLE FACE LOSS FACTOR	(187)	(K_1)	
0	WIDTH OF SLOT OPENING	(135)	b_{bo}	DAMPER BAR
	HEIGHT OF SLOT OPENING	(135)	h_{bo}	
	DAMPER BAR DIA. OR WIDTH	(136)	( )	
	RECTANGULAR BAR THICKNESS	(137)	h_{bl}	
	RECTANGULAR SLOT WIDTH	(135)	b_{bl}	
	NO. OF DAMPER BARS	(138)	n_b	
	DAMPER BAR LENGTH	(139)	b	
	DAMPER BAR PITCH	(140)	b	
	RESISTIVITY OF DAMP. BAR @ 20 °	(141)	D	
0	DAMPER BAR TEMP °C	(142)	X_o °C	
0	FRICTION & WINDAGE	(183)	F & W	
.9	MAGNET RED FACTOR	(508)	C	
10	MAGNET HYST. SLOPE	(519a)	h	
C-24	MAGNET MATERIAL AL. VI	(18)		MTR'L
C-12	ROTOR HEAD LAM SOLID	(18)		
C-11-C	STATOR LAM. MATERIAL M 22	(18)		
C-17	P_o / P_m CURVE DATA	( )		

Curve No. 5 Section F

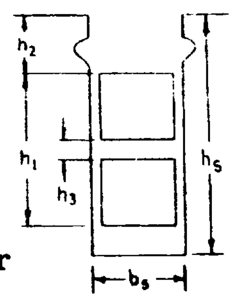
STATOR SLOT	POLE
DAMPER SLOT	REMARKS

DESIGNER

DATE

REV. A

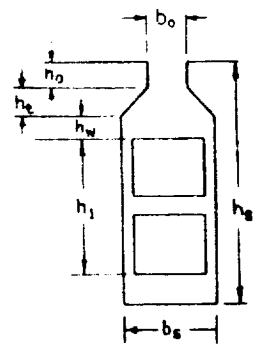
(a) Open Slots



TYPE 1

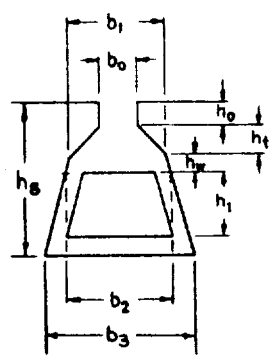
(Type 5 is an open slot with 1 conductor per slot)

(b) Constant Slot Width



TYPE 2

(c) Constant Tooth Width

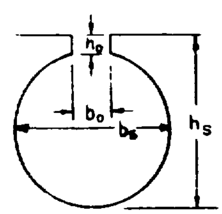


TYPE 3

b_s for type 3 is

$$b_s = \left(\frac{b_1 + b_3}{2}\right)$$

(d) Round Slots



TYPE 4

(OUTPUT)

MODEL E40

STATOR	( ) ($_e$) SOLID CORE LENGTH	1.49500	1.20930	CARTER COEFFICIENT	(67) (K_s)	CONSTANTS
	(24) (h_c) DEPTH BELOW SLOT	.38500	19.14656	AIR GAP AREA	(68) (-)	
	(26) ($_s$) SLOT PITCH	.32729	193.96247	AIR GAP PERM	(70a) ($_g$)	
	(27) ($_s$1/3) SLOT PITCH 1/3 DIST. UP	.35698	.02055	EFFECTIVE AIR GAP	(69) (g_e)	
	(42) (K_{sk}) SKEW FACTOR	1.00000	1.07500	FUND/MAX OF FLD. FLUX	(71) (C_1)	
	(43) (K_d) DIST. FACTOR	.96591	.41900	WINDING CONST.	(72) (C_w)	
	(44) (K_p) PITCH FACTOR	.96596	.65700	POLE CONST.	(73) (C_p)	
	(45) ($_a$) EFF. CONDUCTORS	625.94000	3.66032	END. EXT. ONE TURN	(48) (L_E)	
	(46) (a_c) COND. AREA	.00202	.84000	DEMAGNETIZING FACTOR	(74) (C_M)	
	(47) (S_a) CURRENT DENSITY (STA.)	2468.10000	.61000	CROSS MAGNETIZING FACTOR	(75) (C_q)	
	(49) ($_t$) 1/2 MEAN TURN LENGTH	5.28530	265.62000	AMP COND/IN	(128) (A)	REACTANCE
	(53) (R_{ph}) COLD STA. RES. @ 20° C	.39110	.98245	REACTANCE FACTOR	(129) (X)	
	(54) (R_{ph}) HOT STA. RES. @ X C	.47691	12.89013	LEAKAGE REACTANCE	(130) (X_a)	
	(55) (EFtop) EDDY FACTOR TOP	1.00000	40.71703	SYN REACT DIRECT AXIS	(133) (X_d)	
	(56) (EFbot) EDDY FACTOR BOT	1.00000	.00000	DAMPER	(163) (X_{Dd})	
	(62) ($_l$) STATOR COND. PERM.	5.33720	.00000	LEAKAGE REACT	(165) (X_{Dq})	
	(64) ($_e$) END PERM.	7.78310	12.89000	UNSAT. TRANS. REACT	(166) (X'_{du})	
	(65) ( ) WT. OF STA COPPER	2.22710	11.34300	SUB. TRANS. REACT DIRECT AX.	(168) (X''_d)	
	(66) ( ) WT. OF STA IRON	3.82910	11.34300	SUB. TRANS. REACT QUAD AX.	(169) (X''_q)	
	(41) ($_p$) POLE PITCH	1.96370	5.67160	NEG. SEQUENCE REACT	(170) (X_2)	
	(509) P_i PERMEANCE IN STATOR	16.79500	8.61000	ZERO SEQUENCE REACT	(172) (X_0)	
	(510) P_o PERMEANCE OUT STATOR	23.60000	328.86000	TOTAL FLUX	(88) (ϕ_t)	
	(507) P_m PERMEANCE MAGNET	.90055	36.01000	FLUX PER POLE	(92) (ϕ_p)	
	(511) P_g PERMEANCE AIR GAP	162.55000	17.17500	GAP DENSITY	(95) (B_g)	
	(157) ( ) WT. OF ROTOR IRON	.00000	40.66400	TOOTH DENSITY	(91) (B_t)	
	WT. OF MAGNETS	2.24050	31.28200	CORE DENSITY	(94) (B_c)	
	(145) (V_r) PERIPHERAL SPEED	7788.70000	18.42701	SHORT CIRCUIT AMPS	(522) (I_{sc})	

	(ϕ_{pt}) (102a) POLE FLUX	36.01000			
	(B_p) (103a) POLE DENSITY	24.62200			
LOSSES @ NL	(F&W) (183) F&W LOSS	77.99700	77.99700	(F&W) (183)	LOSSES @ FL
	(W_{tnl}) (184) STA TOOTH LOSS	7.73540	8.02617	(W_{tfl}) (242)	
	(W_c) (185) STA CORE LOSS	10.32300	10.32300	(W_c) (185)	
	(W_{pnl}) (186) POLE FACE LOSS	59.56300	98.92551	(W_{pfl}) (243)	
	(W_{dnl}) (193) DAMPER LOSS	.00000	.00000	(W_{dfl}) (244)	
	(I^2R_s) (194) STATOR CU LOSS	.00000	35.76800	(I^2R_s) (245)	
	(-) (195) EDDY LOSS	.00000	.00000	(-) (246)	
	(-) (196) TOTAL LOSSES	155.61840	231.03968	(-) (247)	
	(-) (-) RATING (KW)	.00000	.99590	(-) (248)	
	(-) (-) RATING & LOSSES	.15561	1.22693	(-) (249)	
	(-) (-) PERCENT LOSSES	100.00000	18.83056	(-) (250)	
	(-) (-) PERCENT EFF.	.00000	81.16944	(-) (251)	

VOLT AMPERE CHARACTERISTIC	VOLTS @ 0 LOAD AMPS	99.78900
	VOLTS @ 1/4 LOAD AMPS	98.92900
	VOLTS @ 1/2 LOAD AMPS	97.60700
	VOLTS @ 3/4 LOAD AMPS	95.81200
	VOLTS @ 4/4 LOAD AMPS	93.52800
	VOLTS @ 5/4 LOAD AMPS	90.72900
	VOLTS @ 3/2 LOAD AMPS	87.37800

REV. B

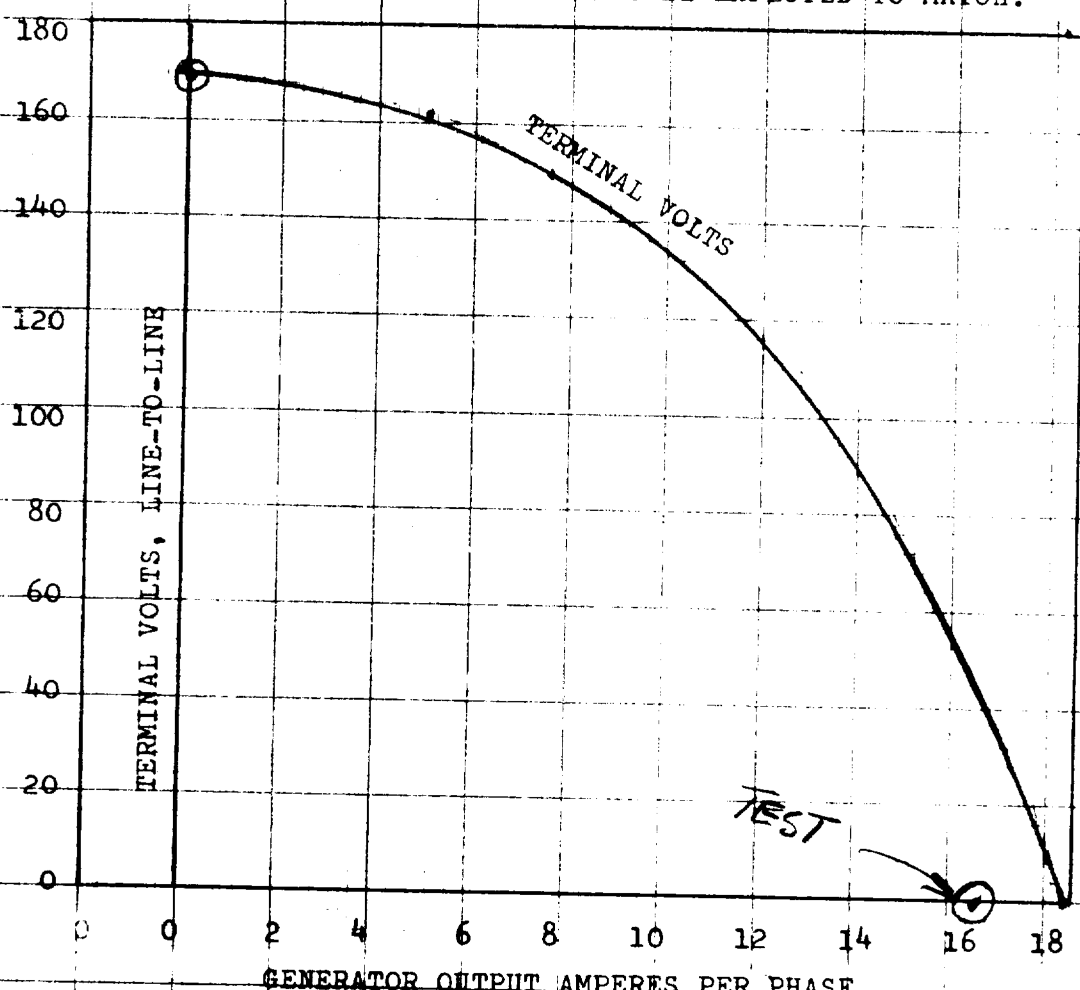
INPUT PARAMETERS FOR PERMANENT MAGNET DESIGN

1.05	115.	66.5	3.	400.	6.	8000.	5.	1.0	3.75
5.54	1.625	0.	0.	.92	15.	77.4	3.	.090	.186
.19	.266	.226	.031	0.	0.	0.	.51	.05	0.
36.	1.	0.	18.	5.	1.	.0508	1.	1.	0.
.25	.25	0.	0.	60.	0.	75.	.694	.017	.02
1.075	.419	.657	0.	.84	.61	1.38	1.	.182	.812
1.625	1.625	.71	3.716	1.	0.	7.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	.9	10.

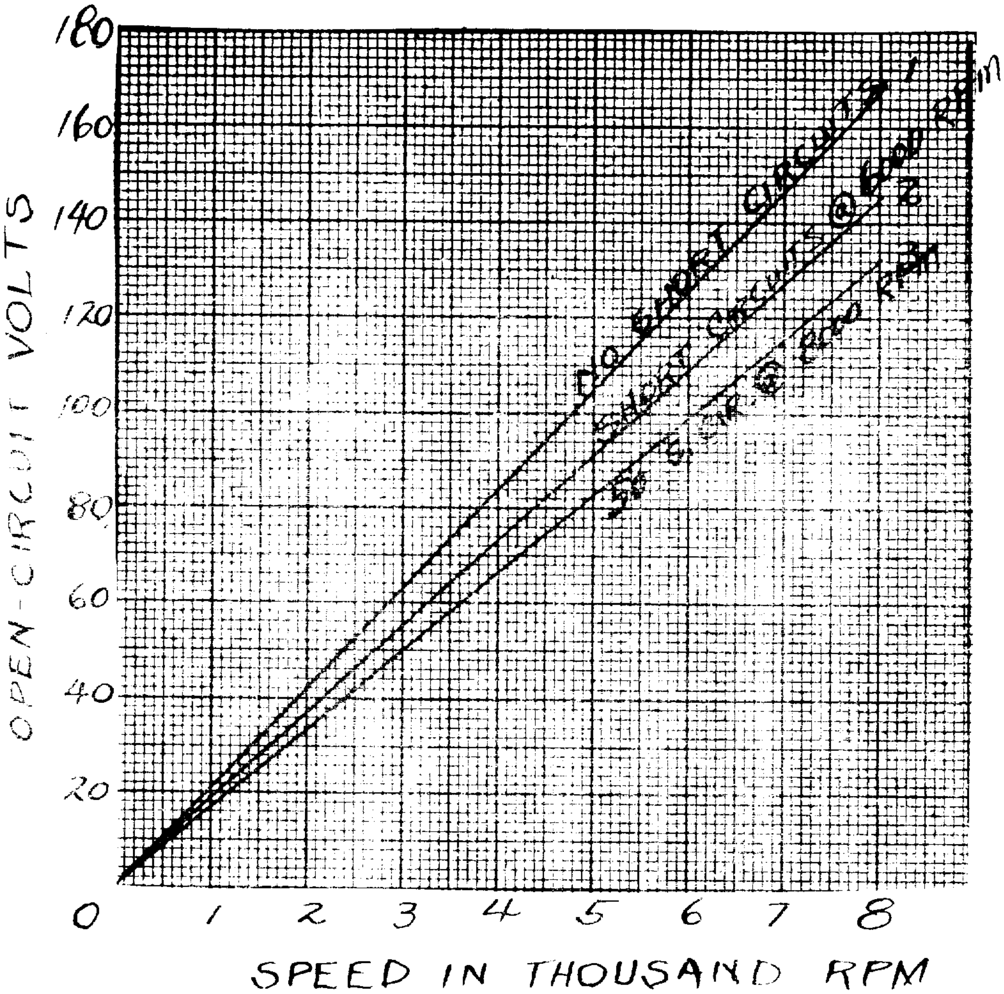
PO/PM CURVE

340.	0.	1500.	20.	1250.	32.
1100.	35.	1000.	85.	640.	130.
500.	150.	385.	187.	315.	257.
280.	340.	200.			

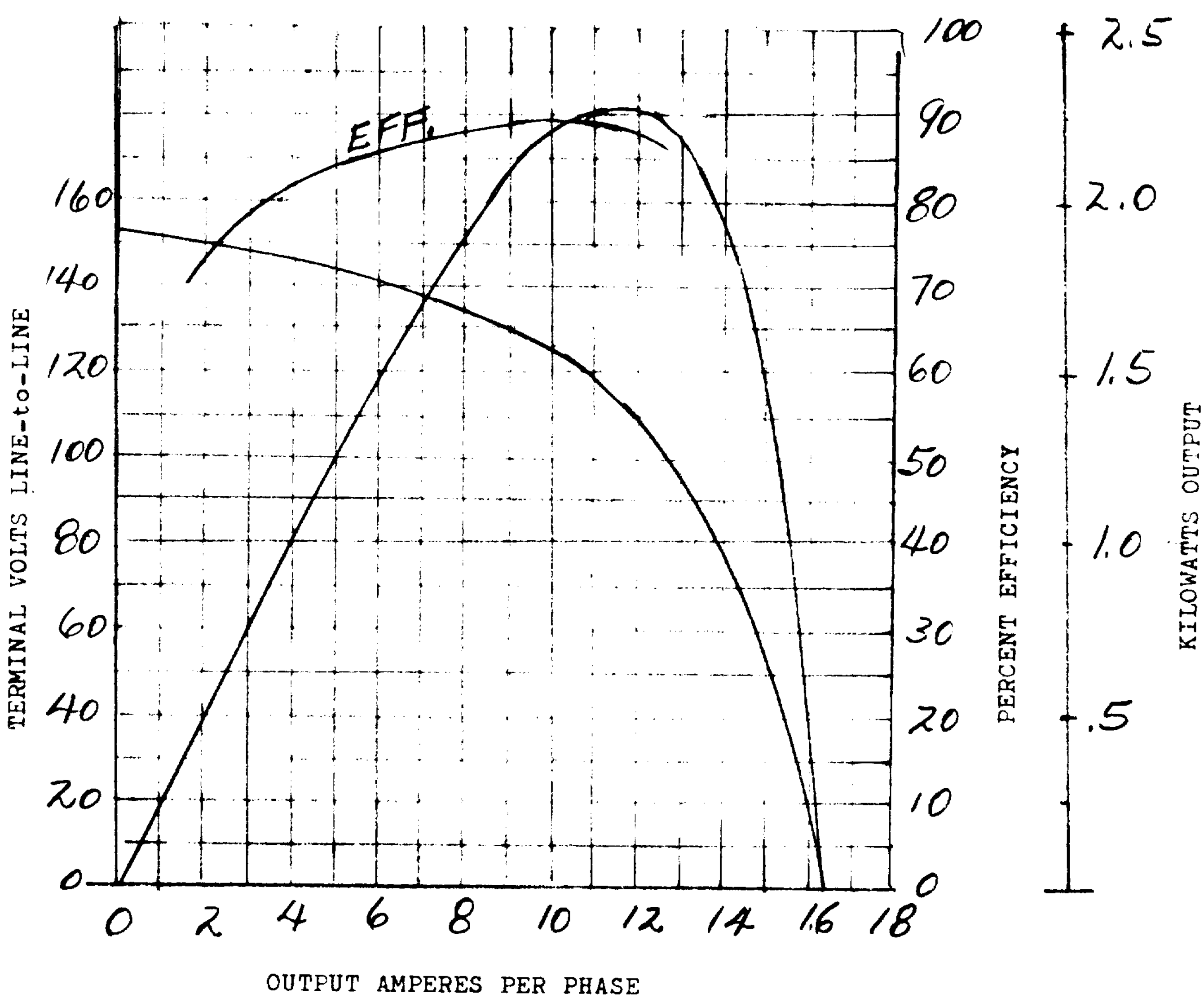
CALCULATED AND TEST PERFORMANCE FOR A PERMANENT MAGNET A-C GENERATOR BEFORE SHORT-CIRCUITING. THE TEST POINT AT SHORT CIRCUIT WAS OBTAINED AT 6000 RPM AND SINCE THE GENERATOR DEMAGNETIZED SLIGHTLY UPON SHORT-CIRCUIT, THE CALCULATED POINT AND THE TEST POINT CANNOT BE EXPECTED TO MATCH.

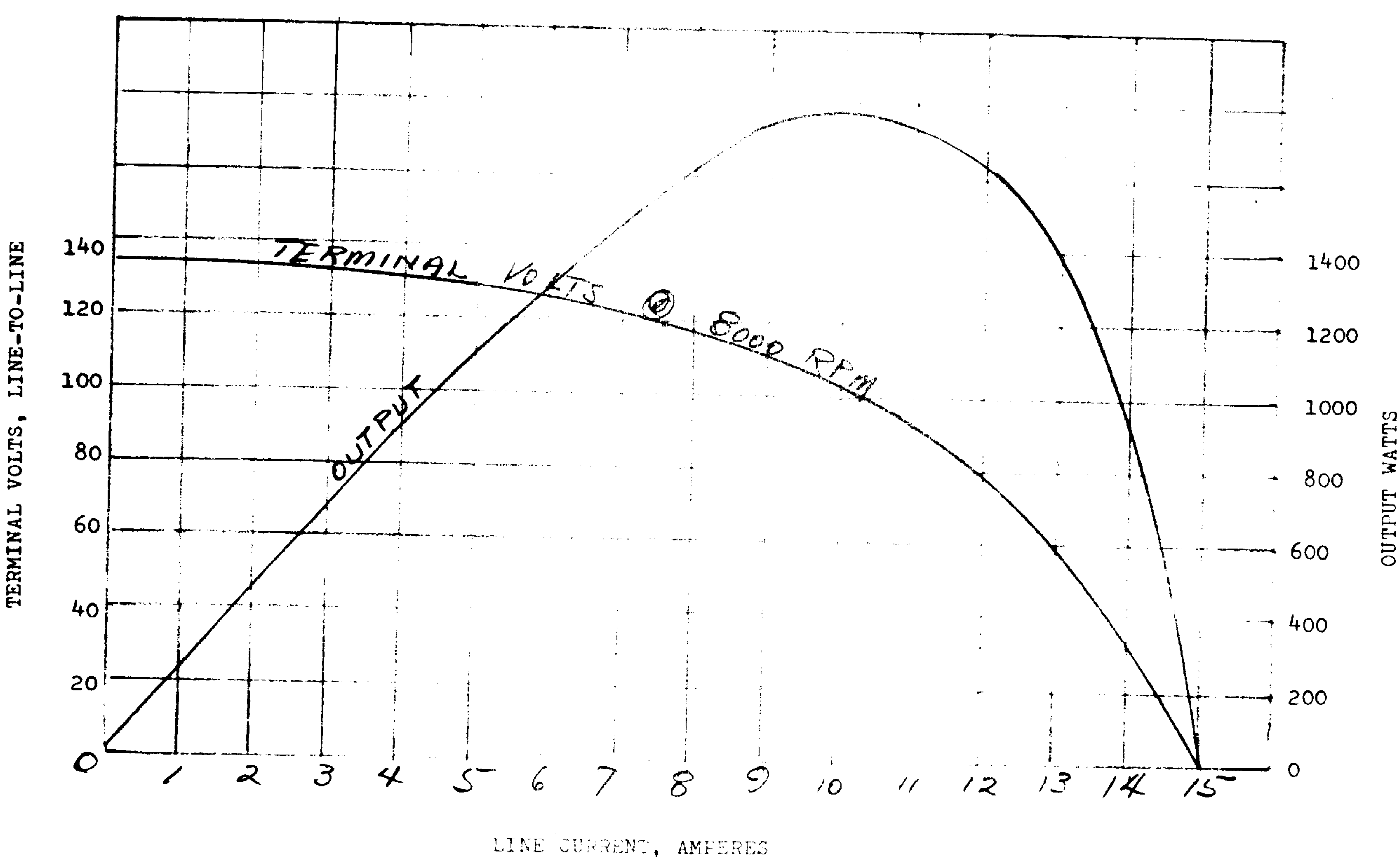


TESTS SHOWING THE EFFECT
OF SHORT-CIRCUITS ON THE
OUTPUT VOLTAGE OF THE
EXAMPLE PERMANENT MAGNET
A-C GENERATOR

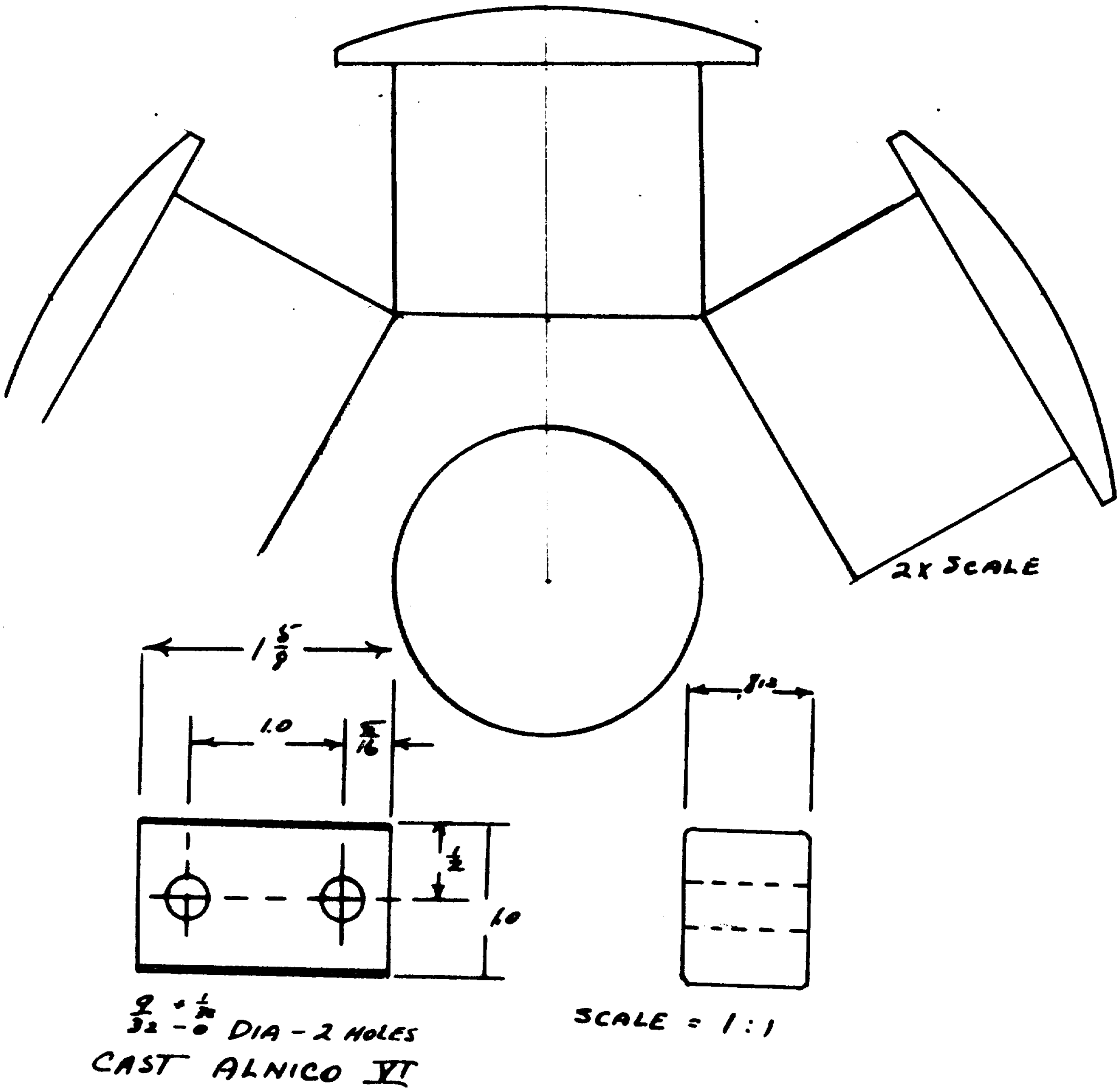


TEST PERFORMANCE OF A P.M.G. AT 8000 RPM
GENERATOR WAS SUPPLYING A RESISTIVE LOAD
AND HAD BEEN SHORT-CIRCUIT STABILIZED AT
6000 RPM





P.M. GENERATOR OUTPUT CHARACTERISTIC AFTER THE GENERATOR WAS SHORT-CIRCUITED 50 TIMES


2X SCALE
1 5/8
1.0
5/16
1/2
1.0
.812
9/32 +1/32 -0 DIA - 2 HOLES
CAST ALNICO VI
SCALE = 1:1

COMPUTER PROCEDURE FOR

PERMANENT MAGNET DESIGN CALCULATIONS

1. Clear core (no switch control).
2. Insert output Form #1 into typewriter, set margin for correct output, and set typewriter for single spacing.
3. Load pass #1 followed by input parameters (output punched cards).
4. Load pass #2 followed by output from pass #1 (output printed plus punched cards).
5. Load pass #3 followed by output from pass #2 (output printed plus punched cards).
6. Load pass #4 followed by output from pass #3 (output punched cards).
7. Load pass #5 followed by output from pass #4 (output punched cards).
8. Load pass #6 followed by PO/FIN values, and output from pass # 5 (output punched cards).
9. Load pass #7 followed by output from pass #6 (output printed and punched cards).
10. Load pass #8 followed by output from pass #7 (output printed).

ALL INPUT PARAMETERS ARE IN FORMAT F7.0 (FIG. 1)

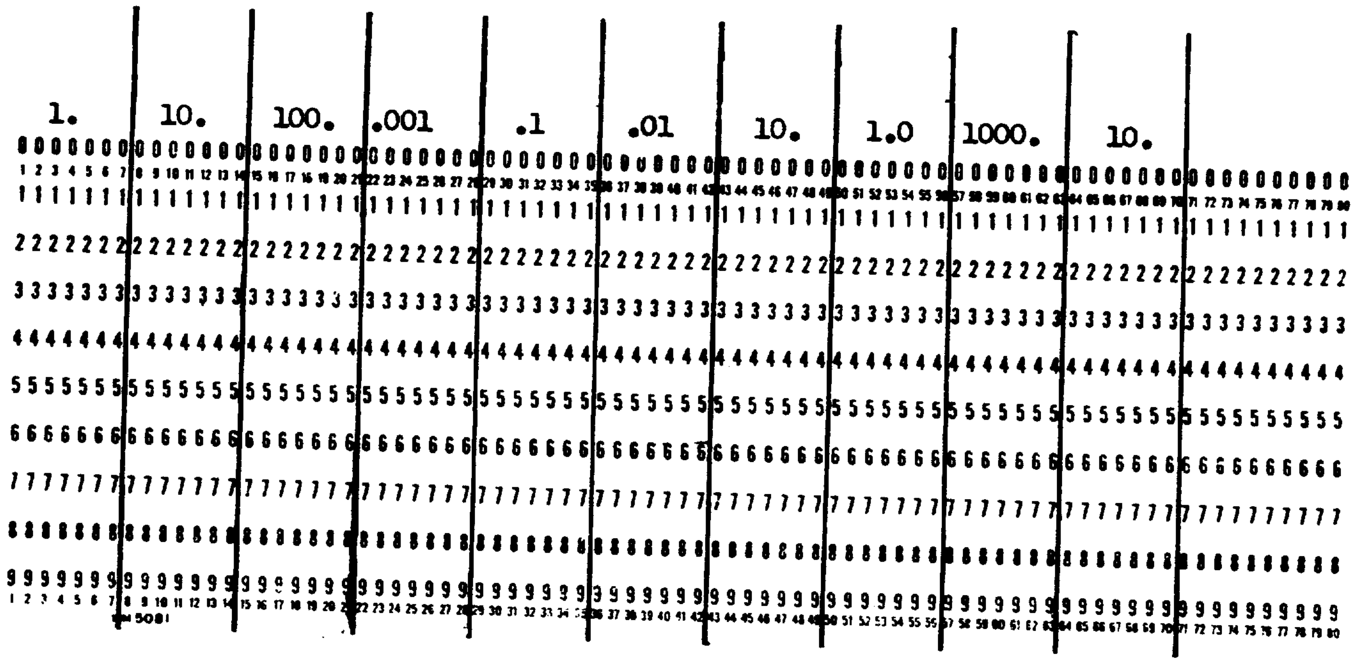


FIG. 1

ALL SATURATION CURVE VALUES ARE IN FORMAT F10.0 (FIG. 2)
(ALL SATURATION CURVES MUST HAVE 5 CARDS)

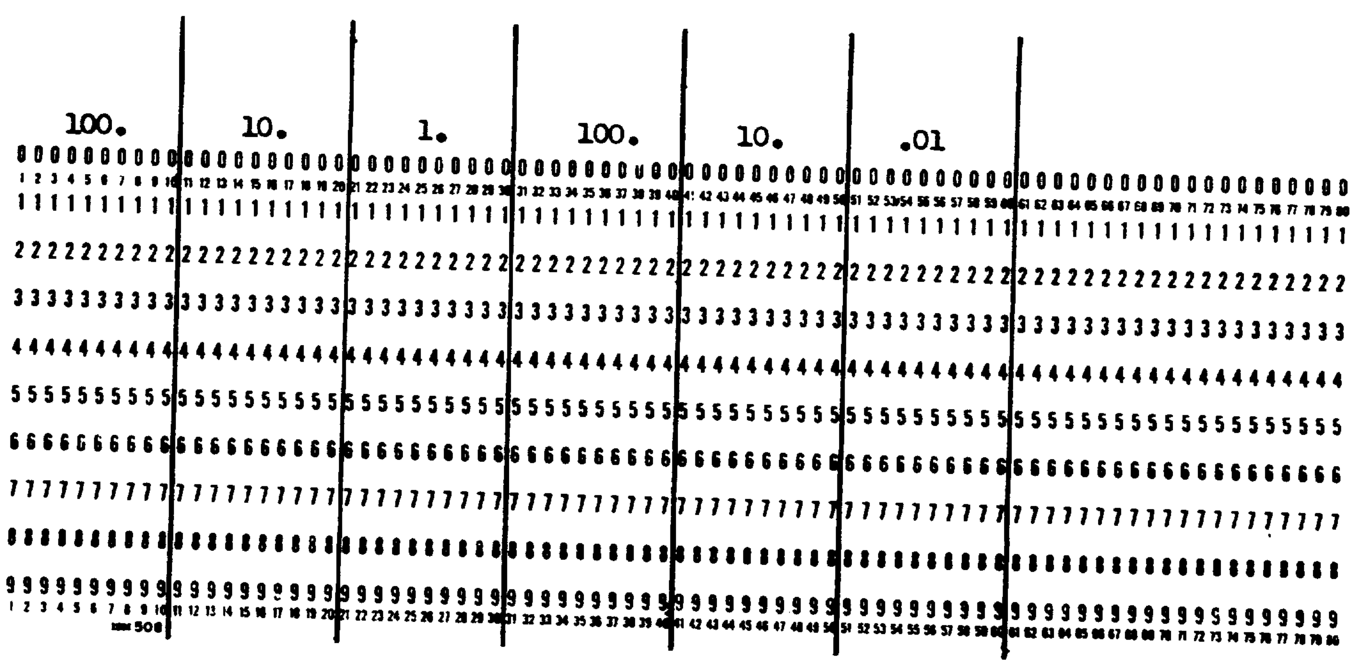


FIG. 2

PERMANENT MAGNET GENERATOR

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	A, a	
(46)	A_c	AC
(68)	A_g	GA
(79)	A_p	AP
(128)	A	A
(501)	a_1	A1
(502)	a_2	A2
(516)	A_T	Y
(519)	A_x	AX
(520)	A_1	A1
	B, b	
(15)	b_v	BV
(20)	B	BK
(22)	b_o	BO
(22)	b_1	B1
(22)	b_2	B2
(22)	b_3	B3
(22)	b_s	BS
(57)	b_{tm}	TM

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(57a)	$b_{t1/3}$	SM
(76)	b_p	BP
(91)	B_t	TE
(94)	B_c	BX
(95)	B_g	FH

C, c

(32)	C	C
(60)	C_x	CX
(71)	C_1	C1
(72)	C_w	CW
(73)	C_p	CP
(74)	C_m	CM
(75)	C_q	CQ
(508)	C	ACM

D, d

(11)	d	DI
(11a)	d_r	DR
(12)	D	DU
(35)	d_b	DB

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	E, e	
(3)	E	EE
(4)	E_{PH}	EP
(55)	E_F (top)	ET
(56)	E_F (bot)	EB
(516)	E_{NL}	ENL
(525)	E_{FL}	EL
	F, f	
(5a)	f	F
(96)	F_g	FH
(183)	F & W	WF
	G, g	
(69)	g_e	GE
(59)	g_{min}	GC
(59g)	g_{max}	GP
	H, h	
(22)	h_o	HO
(22)	h_1	HI

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(22)	h_2	HY
(22)	h_3	HZ
(22)	h_s	HS
(22)	h_t	HT
(22)	h_w	HW
(24)	h_c	HC
(37)	h_{st}	SH
(38)	h'_{st}	SD
(137)	h_{bl}	H
(76)	h_h	HH
(76)	h_f	HF
(519a)	h	AH

I, i

(8)	I_{PH}	PI
(245)	I^2R	PS

K, k

(2)	K_{VA}	VA
(16)	K_i	RK
(19)	k	WL
(42)	K_{sk}	FS

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(43)	K_d	DF
(44)	K_p	CF
(61)	K_x	FF
(63)	K_E	EK
(67)	K_s	CC
	L, l	
(13)	l	L
(17)	l_s	SS
(36)	l_{e2}	CE
(48)	L_E	EL
(49)	l_t	HM
(76)	l_p	PL
(139)	l_b	SB
	M, m	
(5)	m	PN
	N, n	
(14)	n_v	HV
(30)	n_s	SC
(34)	N_{st}	SN

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
(34a)	N'_{st}	SN1
(45)	n_e	EC
(138)	n_b	BN

<u>P, p</u>

(6)	P	PX
(9)	P_F	PF
(500)	P_1	P1
(503)	P_2	P2
(504)	P_3	P3
(505)	P_{s1}	PS1
(506)	P_{s2}	PS2
(507)	P_m	PM
(509)	P_i	PII
(510)	P_o	PO
(511)	P_g	PG

<u>Q, q</u>

(23)	Q	QQ
(25)	q	QN

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	R, r	
(7)	R_{PM}	RPM
(53)	R_{SPH}	RG
(54)	R_{SPH} (Hot)	RP
	S, s	
(47)	S_s	S
	V, v	
(145)	v_r	VR
	W, w	
(184)	W_{TNL}	WT
(185)	W_L	WQ
(186)	W_{NPL}	WN
(193)	W_{DNL}	WD
(242)	W_{TFL}	ST
(243)	W_{PFL}	PP
(244)	W_{DFL}	DL

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	X, x	
(50)	X_s °C	T1
(129)	X	XR
(130)	X_e	XL
(142)	X_D °C	T3
(163)	X_{Dd}	X1
(165)	X_{Dq}	X2
(166)	X'_{DU}	XU
(167)	X'_d	XS
(168)	X''_d	XX
(170)	X_2	XN
(523)	X_d ohms	XD
	Y, y	
(31)	y	YY
	τ	
(26)	τ_s	TS
(27)	$\tau_{s1/3}$	TT
(40)	τ_{sk}	SK
(41)	τ_p	TP
(140)	τ_b	TB

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	$\underline{\lambda}$	
(62)	λ_i	PC
(64)	λ_E	EW
(70c)	λ_a	AG
(80b)	λ_{sl}	SL
(81b)	λ_{tl}	TL
(82b)	λ_{el}	ES
	$\underline{\phi}$	
(88)	ϕ_T	TG
(92)	ϕ_p	FQ
	$\underline{\ell}$	
(51)	ℓ_s	RS
(141)	ℓ_D	RE
	$\underline{\alpha}$	
(77)	α	PE
	$\underline{\theta}$	
(198a)	θ	AN

CALCULATION NUMBER	ELECTRICAL SYMBOL	FORTRAN SYMBOL
	K	
(187)	K_1	D1
(188)	K_2	D2
(189)	K_3	D3
(190)	K_4	D4
(191)	K_5	D5
(192)	K_6	D6

```
C     PASS 1 PERMANENT MAGNET
      DIMENSION DA(8),DX(6),DY(8),DZ(8)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    2 FORMAT(F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0)
   33 READ2,VA,EE,EP,PN,F,PX,RPM,PI,PF,DI
      READ2,DU,CL,HV,BV,SF,WL,BK,ZZ,BO,B1
      READ2,B2,B3,BS,HO,HX,HY,HZ,HS,HT,HW
      READ2,QQ,W,RF,SC,YY,C,DW,SN,SN1,DW1
      READ2,DB,CE,SH,SD,PBA,SK,T1,RS,GC,GP
      READ2,C1,CW,CP,EL,CM,CQ,BH,BP,HH,HF
      READ2,PL,ALN,PE,DR,RK,WR,D1,WO,HD,DD
      READ2,H,B,BN,SB,TB,RE,T3,WF,ACM,AH
      SS=SF*(CL-HV*BV)
      HC=(DU-DI-2.0*HS)*0.5
      ZY=0.7*HS
      IF(HC-ZY) 33,33,5
    5 QN=QQ/(PX*PN)
      TS=3.142*DI/QQ
      IF(ZZ-4.0)29,30,29
   29 TT=(0.667*HS+DI)*3.142/QQ
      GO TO 31
   30 TT=3.1416*(DI+2.*HO+1.32*BS)/QQ
   31 IF(ZZ-1.0)6,6,7
    6 BO=BS
      CC=(5.0*GC+BS)*TS/((5.0*GC+BS)*TS-BS*BS)
      GO TO 8
    7 QC=(4.44*GC+0.75*BO)*TS
      CC=QC/(QC-BO*BO)
    8 CS=YY/(PN*QN)
```

```
      TP=3.142*DI/PX
      IF(SK)32,32,92
   32 FS=1.0
      GO TO 34
   92 FS=SIN(1.571*SK/TP)*TP/(1.571*SK)
   34 IF(PBA-60.)9,9,10
    9 D=1.0
      GO TO 95
   10 D=2.0
   95 I=QN
      U=I
      IF(QN-U)36,36,35
   35 U=PX*PN
      XX=U
      N=U
      DO 11 K=1,N
      Z=U/XX
      I=Z
      Z1=I
      IF(Z-Z1)12,12,11
   12 ZY=QQ/XX
      I=ZY
      Z1=I
      IF(ZY-Z1)37,37,11
   11 XX=XX-1.
   36 ZY=QN
   37 DF=SIN(1.571*D/PN)/(ZY*D*SIN(1.571/(PN*ZY)))
      CF=SIN(YY*1.571/(PN*QN))
      EC=QQ*SC*CF*FS/C
```

```
      DT=DW1
      IF(DT) 13,13,14
13    AC=0.785*DW*DW*SN1
      GO TO 28
14    ZY=0.0
      DA(1)=0.05
      DA(2)=0.072
      DA(3)=0.125
      DA(4)=0.165
      DA(5)=0.225
      DA(6)=0.438
      DA(7)=0.688
      DA(8)=1.5
      DX(1)=0.000124
      DX(2)=0.00021
      DX(3)=0.00021
      DX(4)=0.00084
      DX(5)=0.00189
      DX(6)=0.00189
      DY(1)=0.000124
      DY(2)=0.000124
      DY(3)=0.00084
      DY(4)=0.00084
      DY(5)=0.00189
      DY(6)=0.00335
      DY(7)=0.00754
      DY(8)=0.03020
      DZ(1)=0.000124
      DZ(2)=0.000124
```

```
      DZ(3)=0.000124
      DZ(4)=0.00335
      DZ(5)=0.00335
      DZ(6)=0.00754
      DZ(7)=0.0134
      DZ(8)=0.0302
   93 IF(DT-.05)94,94,15
   15 JA=0
      JB=0
      JC=0
      JD=0
   16 JA=JA+1
      JB=JB+1
      JC=JC+1
      JD=JD+1
      IF(DT-DA(JA))17,17,16
   94 D=0
      GO TO 23
   17 IF(DW-0.188)18,18,19
   18 CY=DX(JB-1)
      CZ=DX(JB)
      GO TO 22
   19 IF(DW-0.75)20,20,21
   20 CY=DY(JC-1)
      CZ=DY(JC)
      GO TO 22
   21 CY=DZ(JD-1)
      CZ=DZ(JD)
   22 D=CY+(CZ-CY)*(DT-DA(JA-1))/(DA(JA)-DA(JA-1))
```

```
23 AC=(DT*DW-D)*SN1
28 S=PI/(C*AC)
   PUNCH1,VA,EE,EP,PN,F,PX
   PUNCH1,RPM,PI,PF,DI,AC,S
   PUNCH1,DU,CL,SS,HC,SF,QN
   PUNCH1,WL,BK,ZZ,BO,B1,B2
   PUNCH1,B3,BS,HO,HX,HY,HZ
   PUNCH1,HS,HT,HW,QQ,W,RF
   PUNCH1,SC,YY,C,TS,SN,DB
   PUNCH1,CE,SH,SD,TT,SK,T1
   PUNCH1,RS,GC,GP,C1,CW,CP
   PUNCH1,EL,CM,CQ,BH,BP,HH
   PUNCH1,HF,PL,ALN,PE,DR,RK
   PUNCH1,CC,WR,D1,WO,HD,DD
   PUNCH1,H,B,BN,SB,TB,RE
   PUNCH1,T3,WF,CS,FS,TP,DF
   PUNCH1,CF,EC,ACM,AH,PBA
   PAUSE
   END
```

```
C      PASS 2 PERMANENT MAGNET
     1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
     3 FORMAT(9X F12.5,2X F12.5)
       READ1, VA,EE,EP,PN,F,PX
       READ 1,RPM,PI,PF,DI,AC,S
       READ1, DU,CL,SS,HC,SF,QN
       READ1, WL,BK,ZZ,BO,B1,B2
       READ1, B3,BS,HO,HX,HY,HZ
       READ1, HS,HT,HW,QQ,W,RF
       READ1, SC,YY,C,TS,SN,DB
       READ1, CE,SH,SD,TT,SK,T1
       READ1, RS,GC,GP,C1,CW,CP
       READ1, EL,CM,CQ,BH,BP,HH
       READ 1,HF,PL,ALN,PE,DR,RK
       READ1, CC,WR,D1,WO,HD,DD
       READ1, H,B,BN,SB,TB,RE
       READ 1,T3,WF,CS,FS,TP,DF
       READ 1,CF,EC,ACM,AH,PBA
       GA=3.142*DI*CL
       AG=6.38*DI/(PX*GC*CC)
       GE=CC*GC
       IF(C1) 44,43,44
    43 C1=(0.649*LOG(PE)+1.359)*((GC/GP)**0.352)
    44 IF(CW)45,45,46
    45 CW=0.707*EE*C1*DF/(EP*PN)
    46 TG=6000000.0*EE/(CW*EC*RPM)
       BG=TG/GA
       IF(CP)47,47,48
    47 CP=(GC/GP)**0.41*PE*(LOG(GC/TP)*.0378+1.191)
```

```
48 FQ=TG*CP/PX
   IF(ZZ-3.0)49,50,51
49 SM=TT-BS
   GO TO 53
50 SM=(3.1416*(DI+2.*HS)/QQ)-B3
   GO TO 53
51 IF(ZZ-4.0)50,52,49
52 SM=TT-.94*BS
53 TE=TG/(QQ*SS*SM)
   BX=0.5*FQ/(HC*SS)
   IF(EL) 54,54,62
54 IF(RF) 55,55,61
55 IF(PX-2.0) 56,56,57
56 U=1.3
   GO TO 60
57 IF(PX-4.0) 58,58,59
58 U=1.5
   GO TO 60
59 U=1.7
60 EL=3.142*U*YY*(DI+HS)/QQ+0.5
   GO TO 62
61 EL=2.0*CE+(3.142*(0.5*HX+DB))+(YY*TS*TS/(SQRT(TS*TS-BS*BS)))
62 HM=CL+EL
   RY=SC*QQ*HM/(PN*AC*C*C)
   RX=RS*0.000001
   RB=(T1+234.5)*0.00394*RX
   RG=RX*RY
   RP=RB*RY
   IF(SH)37,38,40
```

```
38 ET=1
   EB=1
   GO TO 39
40 AA=0.584+(SN*SN-1.0)*0.0625*(SD*CL/(SH*HM))*2.0
   AB=(SH*SC*F*AC/(BS*RB*1000000.0))**2.0
   ET=AA*AB*0.00335+1.0
   EB=ET-0.00168*AB
39 IF(CM)63,63,64
63 AA=SIN(3.142*PE)
   AB=SIN(1.571*PE)*4.0
   CM=(3.142*PE+AA)/AB
64 A=PI*SC*CF/(C*TS)
   PRINT3,SS,CC,HC,GA,TS,AG,TT,GE,FS,C1,DF,CW,CF,CP,EC,EL,AC,CM
   PUNCH1,VA,EE,EP,PN,F,PX
   PUNCH1,RPM,PI,PF,DI,ACM
   PUNCH1,DU,CL,SS,HC,SF,QN
   PUNCH1,WL,BK,ZZ,BO,B1,B2
   PUNCH1,B3,BS,HO,HX,HY,HZ
   PUNCH1,HS,HT,HW,QQ,W,GE
   PUNCH1,SC,YY,C,TS,BG,TG
   PUNCH1,FQ,TE,BX,TT,HM,SM
   PUNCH1,RG,GC,RP,C1,CW,CP
   PUNCH1,EL,CM,CQ,BH,BP,HH
   PUNCH1,HF,ALN,PL,PE,DR,RK
   PUNCH1,CC,WR,D1,WO,HD,DD
   PUNCH1,H,B,BN,SB,TB,RE
   PUNCH1,T3,WF,CS,ET,AH,EC
   PUNCH1,TP,DF,CF,EB,AC,S
   PUNCH1,AG,A,SM,PBA
```

```
PAUSE
END
```

```
C     PASS 3 PERMANENT MAGNET
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    3 FORMAT(9X F12.5,2X F12.5)
      READ1, VA,EE,EP,PN,F,PX
      READ 1,RPM,PI,PF,DI,ACM
      READ1, DU,CL,SS,HC,SF,QN
      READ1, WL,BK,ZZ,BO,B1,B2
      READ1, B3,BS,HO,HX,HY,HZ
      READ1, HS,HT,HW,QQ,W,GE
      READ1, SC,YY,C,TS,BG,TG
      READ1, FQ,TE,BX,TT,HM,SM
      READ1, RG,GC,RP,C1,CW,CP
      READ1, EL,CM,CQ,BH,BP,HH
      READ 1,HF,ALN,PL,PE,DR,RK
      READ1, CC,WR,D1,WO,HD,DD
      READ1, H,B,BN,SB,TB,RE
      READ 1,T3,WF,CS,ET,AH,EC
      READ1, TP,DF,CF,EB,AC,S
      READ 1,AG,A,SM,PBA
      IF(CQ)69,69,70
   69 AA=1.571*PE
      AB=3.1416*PE
      CQ=(0.5*COS(AA)+AB-SIN(AB))/(4.0*SIN(AA))
   70 XR=.0707*A*DF/(C1*BG)
      IF(ZZ-5.)350,351,350
  351 FF=1.0
      GO TO 75
  350 IF(PBA-60.)352,353,352
  353 IF(CS-.667)354,355,355
```

```
355 D=.75
    Z=.25
    GO TO 74
354 D=1.5
    Z=-.25
    GO TO 74
352 IF(CS-.667)356,357,357
357 FF=.75
    GO TO 75
356 D=1.2
    Z=-.05
 74 FF=D*CS+Z
 75 CX=FF/(CF*CF*DF*DF)
    Z=CX*20.0/(PN*QN)
    BT=3.142*DI/QQ-BO
    ZA=BT*BT/(16.0*TS*GC)
    ZB=0.35*BT/TS
    ZC=HO/BO
    ZD=HX*0.333/BS
    ZE=HY/BS
    IF(ZZ-2.0) 76,77,78
 76 PC=Z*(ZE+ZD+ZA+ZB)
    GO TO 82
 77 PC=Z*(ZC+(2.0*HT/(BO+BS))+(HW/BS)+ZD+ZA+ZB)
    GO TO 82
 78 IF(ZZ-4.0) 79,80,81
 79 PC=Z*(ZC+(2.0*HT/(BO+B1))+(2.0*HW/(B1+B2))+(HX*0.333/B2)+ZA+ZB)
    GO TO 82
 80 PC=Z*(ZC+0.62)
```

```
      GO TO 82
   81 PC=Z*(ZE+ZD+(0.5*GC/TS)+(0.25*TS/GC)+0.6)
   82 EK=EL/(10.0**(0.103*YY*TS+0.402))
      IF(DI-8.0) 83,83,84
   83 EK=SQRT(EK)
   84 ZF=.612*LOG(10.0*CS)
      EW=6.28*EK*ZF*(TP**(0.62-(0.228*LOG(ZF))))/(CL*DF*DF)
      IF(PN-3.0)85,86,86
   85 ZC=0.1*DI*SIN(3.0*YY/(PN*QN))*1.57/(PX*GE*CF)
      GO TO 87
   86 ZC=0.0
   87 XL=(PC+EW+ZC)*XR
      XD=XR*AG*C1*CM
      XQ=XR*CQ*AG
      WC=0.321*SC*QQ*AC*HM
      PRINT3,S,CQ,HM,A,RG,XR,RP,XL
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,DI,EC,PE
      PUNCH1,DU,CL,SS,HC,PC,QN
      PUNCH1,WL,BK,ZZ,BO,XD,AH
      PUNCH1,XR,BS,XL,HX,HY,HZ
      PUNCH1,HS,WC,AC,QQ,W,GE
      PUNCH1,SC,YY,C,TS,BG,TG
      PUNCH1,FQ,TE,BX,TT,EW,AG
      PUNCH1,RG,GC,RP,C1,TP,CP
      PUNCH1,DF,CM,CF,BH,BP,HH
      PUNCH1,HF,PL,ALN,EB,DR,RK
      PUNCH1,CC,WR,D1,WO,HD,DD
      PUNCH1,H,B,BN,SB,TB,RE
```

```
PUNCH1,T3,ACM,WF,CS
PUNCH1,ET,SM
PAUSE
END
```

```
C      PASS 4 PERMANENT MAGNET
     3 FORMAT(9X F12.5,2X F12.5)
     1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
       READ1, VA,EE,EP,PN,F,PX
       READ 1,RPM,PI,PF,DI,EC,PE
       READ1, DU,CL,SS,HC,PC,QN
       READ 1,WL,BK,ZZ,BO,XD,AH
       READ1, XR,BS,XL,HX,HY,HZ
       READ1, HS,WC,AC,QQ,W,GE
       READ1, SC,YY,C,TS,BG,TG
       READ1, FQ,TE,BX,TT,EW,AG
       READ1, RG,GC,RP,C1,TP,CP
       READ1, DF,CM,CF,BH,BP,HH
       READ 1,HF,PL,ALN,EB,DR,RK
       READ1, CC,WR,D1,WO,HD,DD
       READ1, H,B,BN,SB,TB,RE
       READ 1,T3,ACM,WF,CS
       READ 1,ET,SM
       ZA=3.1416*(DI+HS)/QQ
       IF(ZZ-3.0) 88,89,88
    88 TM=ZA-BS
       GO TO 90
    89 TM=(3.1416*(DI+2.*HS)/QQ)-B3
    90 WI=(TM*QQ*SS*HS+(DU-HC)*3.142*HC*SS)*0.283
       AN=0.0
   100 AN=AN+0.005
       AL=COS(AN)
       IF(PF-AL) 100,100,101
   101 VR=0.262*DR*RPM
```

```
      AP=BP*PL*ACM
      FH=BG*GE/0.00319
      IF(BN)307,306,307
  306 X1=0
      P2=0
      X2=0
      GO TO 308
  307 IF(DD)103,103,102
  102 ZG=0.62
      GO TO 104
  103 ZG=0.333*H/B
  104 BD=(HD/WO+ZG+0.5)*6.38
      BE=(BH-(BN-1.0)*TB)*2.127/GE
      P1=(BD+BE)*RL*COS((BN-1.0)*TB*1.572/TP)/(BD+BE+RL)
      X1=XR*P1
      P2=(HD/WO+ZG+0.5+GC/TB)*20.0*TB/TP
      X2=XR*P2
  308 XU=XL+XF
      XS=0.88*XU
      IF(BN)105,105,106
  105 XX=XS
      GO TO 107
  106 XX=XL+X1
  107 XN=(XX+XY)*0.5
  110 IF(WF)111,111,112
  111 WF=DR**2.5*(RPM**1.5)*PL*0.00000252
  112 WQ=(DU-HC)*1.42*HC*SS*(BX/BK)**2.0*WL
      WT=(SM)*QQ*SS*HS*0.453*(TE/BK)**2.0*WL
      PUNCH1,VA,EE,EP,PN,F,PX
```

```
PUNCH1,RPM,PI,PF,DI,PC,WC
PUNCH1,DU,CL,SS,HC,PC,QN
PUNCH1,WL,BK,ZZ,BO,XD,WI
PUNCH1,XR,BS,HX,HY,HZ,EC
PUNCH1,HS,AC,QQ,W,GE,HD
PUNCH1,SC,YY,C,TS,BG,TG
PUNCH1,FQ,TE,BX,TT,EW,AG
PUNCH1,RG,GC,RP,C1,AP,P2
PUNCH1,DF,CF,FH,BP,HH,AL
PUNCH1,HF,ALN,PL,EB,DR,RK
PUNCH1,CC,WR,D1,WO,HD,DD
PUNCH1,H,B,BN,SB,TB,RE
PUNCH1,T3,VR,WT,ACM,AH
PUNCH1,WQ,WF,CS,ET,TP,X1
PUNCH1,XX,XN,XL,CM,CP,PE
PUNCH1,X2,XU,XS,AN
PAUSE
END
```

```
C     PASS 5 PERMANENT MAGNET
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    3 FORMAT(9X F12.5,2X F12.5)
      READ1, VA,EE,EP,PN,F,PX
      READ 1,RPM,PI,PF,DI,PC,WC
      READ1, DU,CL,SS,HC,PC,QN
      READ 1,WL,BK,ZZ,BO,XD,WI
      READ 1,XR,BS,HX,HY,HZ,EC
      READ 1,HS,AC,QQ,W,GE,HD
      READ1, SC,YY,C,TS,BG,TG
      READ1, FQ,TE,BX,TT,EW,AG
      READ1, RG,GC,RP,C1,AP,P2
      READ 1,DF,CF,FH,BP,HH,AL
      READ 1,HF,ALN,PL,EB,DR,RK
      READ1, CC,WR,D1,WO,HD,DD
      READ1, H,B,BN,SB,TB,RE
      READ1 ,T3,VR,WT,ACM,AH
      READ 1,WQ,WF,CS,ET,TP,X1
      READ 1,XX,XN,XL,CM,CP,PE
      READ 1,X2,XU,XS,AN
      GT=BO/GC
      IF(GT-1.0)304,304,303
  304 AA=2.6
      GO TO 115
  303 IF(GT-3.75)113,114,114
  113 AA=10.0**0.178/((GT-1.0)**0.334)
      GO TO 115
  114 AA=10.0**0.11/((GT-1.0)**0.174)
  115 GF=AA*PI*SC/(C*FH)
```

```
305 IF(SC-1.0)121,121,122
120 A5=0.0
    GO TO 129
121 AX=1.0
    AY=1.0
    GO TO 125
122 AX=3.0*YY/(PN*QN)-2.0
    IF(CS-0.667)123,124,124
123 AY=1.5*YY/(PN*QN)-0.25
    GO TO 125
124 AY=.75*YY/(PN*QN)+0.25
125 A3=AX*P2/AY
    A4=0.07*AX*AG/(CF*CF)
    IF(AX)120,120,126
126 IF(BN)127,127,128
127 A5=A4
    GO TO 129
128 A5=(A4+A3)/(A3*A4)
129 IF(W)130,130,131
130 XO=0.0
    GO TO 132
131 AA=(3.0*HZ+HX)*1.667/(PN*QN*CF*CF*DF*DF*BS)
    XO=((PC+A5)*AX/AY+AA+0.2*EW)*XR
132 D2=BG**2.5*0.000061
    D3=(0.0167*QQ*RPM)**1.65*0.000015147
    IF(TS-0.9) 133,133,134
133 D4=TS**1.285*0.81
    GO TO 137
134 IF(TS-2.0) 135,135,136
```

```
135 D4=TS**1.145*0.79
    GO TO 137
136 D4=TS**0.79*0.92
137 D7=BO/GC
    IF(D7-1.7) 138,138,139
138 D5=D7**2.31*0.3
    GO TO 144
139 IF(D7-3.0) 140,140,141
140 D5=D7**2.0*0.35
    GO TO 144
141 IF(D7-5.0) 142,142,143
142 D5=D7**1.4*0.625
    GO TO 144
143 D5=D7**0.965*1.38
144 D6=10.0**(0.932*C1-1.606)
    BA=3.142*DI*CL
    WN=D1*D2*D3*D4*D5*D6*BA
    UY=(SL+ES+TL)*ALN*0.00638
    VT=0.
    AA=WO/(GC*CC)
    IF(AA)148,147,148
148 IF(AA-0.65)145,145,146
145 VT=LOG(10.0*AA)*(-0.242)+0.59
    GO TO 147
146 VT=0.327-(AA*0.266)
147 UZ=(DU-HC)*0.7850/PX
    EZ=(ET+EB)*0.5-1.0
    AA=PN*PI*PI
    PU=AA*RG
```

```
WRM=BP*PL*HF*.283*PX
PV=AA*RP
VV=EP*PI*PF*.003
PUNCH1,VA,EE,EP,PN,F,PX
PUNCH1,RPM,PI,PF,TB,BO,GC
PUNCH1,HH,HF,ALN,DR,SB,RE
PUNCH1,T3,WO,DD,H,BN,GF
PUNCH1,VT,TS,CC,BG,AP,FQ
PUNCH1,TE,BX,FH,WQ,WT,AN
PUNCH1,RP,WF,HS,B,GE,BP
PUNCH1,WN,UZ,EZ,PU,VV,XD
PUNCH1,PV,HD,QN,XO,TG,VR
PUNCH1,PC,WC,WR,WI,TP,DI
PUNCH1,X1,X2,XU,XS,ET,EB
PUNCH1,XX,PL,ACM,AH,EW,CM
PUNCH1,PE,AG,XN,CP,CL,EC
PUNCH1,XL,WRM,DF
PAUSE
END
```

```
C     PASS 6 PERMAMENT MAGNET
      DIMENSION AI(30)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
  888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
      K=1
  823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K-29)823,199,199
  199 READ 1,VA,EE,EP,PN,F,PX
      READ 1,RPM,PI,PF,TB,BO,GC
      READ 1,HH,HF,ALN,DR,SB,RE
      READ 1,T3,WO,DD,H,BN,GF
      READ 1,VT,TS,CC,BG,AP,FQ
      READ 1,TE,BX,FH,WQ,WT,AN
      READ 1,RP,WF,HS,B,GE,BP
      READ 1,WN,UZ,EZ,PU,VV,XD
      READ 1,PV,HD,QN,XO,TG,VR
      READ 1,PC,WC,WR,WI,TP,DI
      READ 1,X1,X2,XU,XS,ET,EB
      READ 1,XX,PL,ACM,AH,EW,CM
      READ 1,PE,AG,XN,CP,CL,EC
      READ 1,XL,WRM,DF
      PD=FQ/AP
      Z=COS(3.1416/PX)
      TAN=SIN(3.1416/PX)/Z
      A2=((DI/2.-GC-HH-HF)*TAN-BP/2.)*Z*2.
      A1=((DI/2.-GC-HH)*TAN-BP/2.)*Z*2.
      IF(A2-.2)401,401,400
  401 P1=3.19*PX*PL/3.1416
```

```
      GO TO 402
  400 P1=PL*PX*(1.-(A2/(A1-A2))*LOG(1.+(A1-A2)/A2))*3.19
  402 P2=1.66*(1.+1.23*LOG(1./(1.-PE)))*PL
      P3=HF*1.66*(1.+1.23*LOG(1.+2./((A1+A2)/BP)))
      PS1=6.38*HH*PL/(TP-BP)
      PS2=2.*HH*P2/PL
      PM=PL*BP*ACM/(2.*HF)
      PII=PS1+PS2+P1+P3
      PO=PII+P2
      PG=.785*AG*CP*CL
      PW=PII+PG
      X=PO/PM
      NA=1
      GO TO 802
  805 ENL=.001*(EP*Y/PD)*(PO/PM+AH)*(PW/PM-PII/PM)/(PW/PM+AH)
      PUNCH1,VA,EE,EP,PN,F,PX
      PUNCH1,RPM,PI,PF,TB,BO,GC
      PUNCH1,HH,HF,ALN,DR,SB,RE
      PUNCH1,T3,WO,DD,H,BN,GF
      PUNCH1,VT,TS,CC,BG,FQ,Y
      PUNCH1,TE,BX,FH,WQ,WT,AN
      PUNCH1,WF,HS,B,GE,BP,PW
      PUNCH1,WN,UZ,EZ,PU,VV,PD
      PUNCH1,PV,HD,QN,XO,TG,VR
      PUNCH1,PC,WC,WR,WI,TP,DI
      PUNCH1,X1,X2,XU,XS,ENL,PG
      PUNCH1,XX,PL,AH,EW,RP,PM
      PUNCH1,PE,AG,XN,CP,CL,EC
      PUNCH1,XL,WRM,DF,CM,ET,EB
```

```
      PUNCH1,FQ,BG,TG,BX,TE
      PUNCH1,PII,PO
      PAUSE
  802 IF(AI(NA)-X)830,831,831
  831 NA=NA+3
  835 IF(AI(NA)-X)833,834,834
  833 NA=NA+2
      GO TO 835
  834 AA=AI(NA)
      BB1=AI(NA-2)
      DC=AI(NA+1)
      D=AI(NA-1)
      XXX=(AA-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
      Y=AA-XXX*.4343*LOG(DC)
      Y=EXP(2.306*(X-Y)/XXX)
      GO TO 805
  830 PRINT850
  850 FORMAT(17HMACHINE SATURATED)
      PAUSE
      END
```

```
C     PASS 7 PERMANENT MAGNET
      DIMENSION EL(6)
    3 FORMAT(9X F12.5,2X F12.5)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
      READ 1,VA,EE,EP,PN,F,PX
      READ 1,RPM,PI,PF,TB,BO,GC
      READ 1,HH,HF,ALN,DR,SB,RE
      READ 1,T3,WO,DD,H,BN,GF
      READ 1,VT,TS,CC,BG,FQ,Y
      READ 1,TE,BX,FH,WQ,WT,AN
      READ 1,WF,HS,B,GE,BP,PW
      READ 1,WN,UZ,EZ,PU,VV,PD
      READ 1,PV,HD,QN,XO,TG,VR
      READ 1,PC,WC,WR,WI,TP,DI
      READ 1,X1,X2,XU,XS,ENL,PG
      READ 1,XX,PL,AH,EW,RP,PM
      READ 1,PE,AG,XN,CP,CL,EC
      READ1 ,XL,WRM,DF,CM,ET,EB
      READ 1,FQ,BG,TG,BX,TE
      READ 1,PII,PO
      PW=PII+PG
      AX=Y*(PO/PM+AH)/(PII/PM+AH)
      A1=Y*(PO/PM+AH)/(PW/PM+AH)
      AZ=PI
  326 HD1=.45*AZ*EC*CM*DF/(PX*HF)
      AISC=(ENL*(AX-A1-HD1)/(AX-A1))/SQRT(RP**2+(XL*EP*.01/PI)**2)
      D=AISC-AZ
      IF(D)322,323,323
  322 D=-D
```

```
323 IF(D-.05)324,325,325
325 AZ=(AISC-AZ)/2.+AZ
    GO TO 326
324 XD=ENL/AISC
    XDPU=XD*PI*100./EP
    TPF=SIN(AN)/COS(AN)
    SPF=SIN(1.5708-AN)
    CPF=COS(1.5708-AN)
    Z=.25
    DO 327 K=1,6
    AZ=Z*PI
    X=(AZ*XD-AZ*RP*TPF)
    B=X*SPF/ENL
    B=ATAN(B/SQRT(1.-B**2))
    EL(K)=ENL*COS(B)-X*CPF-AZ*RP/PF
327 Z=Z+.25
    PRINT3,ET,XDPU,EB,X1,PC,X2,EW,XU,WC,XS
    PRINT3,WI,XX,TP,XN,PII,XO,PO,TG,PM,FQ
    PRINT3,PG,BG,WR,TE,WRM,BX,VR,AISC
    PRINT321,FQ
    PRINT3,PD
321 FORMAT (/9X F12.5)
    PUNCH1,F,PX,TB,BO,GC,SB
    PUNCH1,RE,T3,WO,DD,H,BN
    PUNCH1,TS,CC,BG,B,HD,QN
    PUNCH1,EZ,XDPU,WT,WF,WQ,VV
    PUNCH1,ENL,EL(1),EL(2),EL(3),EL(4),EL(5)
    PUNCH1,EL(6),PU,PV,GF,WN
    PAUSE
```

END

```
C     PASS 8  PERMANENT MAGNET GENERATOR
      DIMENSION PR(2),PS(2),G(2),DL(2),PP(2),EX(2),ST(2),VA(2)
      DIMENSION P(2),E(2),PM(2),SP(2),EL(6)
    1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    3 FORMAT(9X,F12.5,2X,F12.5)
      READ 1,F,PX,TB,BO,GC,SB
      READ 1,RE,T3,WO,DD,H,BN
      READ 1,TS,CC,BG,B,HD,QN
      READ1 ,EZ,XDPU,WT,WF,WQ,VV
      READ 1,ENL,EL(1),EL(2),EL(3),EL(4),EL(5)
      READ 1,EL(6),PU,PV,GF,WN
      IF(RE)309,309,311
  309 WD=0.0
      WU=0.0
      GO TO 178
  311 FS1=2.0*QN*PN*F
      FS2=2.0*FS1
      M=0
  150 IF(M-1)151,152,178
  151 RM=RE
      GO TO 153
  152 RM=RE*(T3+234.5)/254.5
  153 AA=(FS1/RM)**0.5*DD*0.32
      AB=(FS2/RM)**0.5*DD*0.32
      IF(AA-2.5) 160,160,161
  160 V1=1.0-0.15*AA+0.3*AA*AA
      GO TO 162
  161 V1=AA
  162 IF(AB-2.5) 163,163,164
```

```
163 V2=1.0-0.15*AB+0.3*AB*AB
    GO TO 165
164 V2=AB
165 IF(H-B) 167,166,167
166 VC=0.75/V1
    GO TO 169
167 IF(DD) 166,168,166
168 VC=H/(3.0*B*V1)
169 VS=HD/WO+VT+VC
    VG=TB/(CC*GC)
    Q1=1.0-(1.0/(((BO*0.5/GC)**2.0+1.0)**0.5))
    QZ=BO/TS
    Q2=1.05*SIN(QZ*2.844)
    IF(QZ-0.37)170,170,171
170 Q3=0.46
    GO TO 172
171 Q3=0.23*SIN(10.46*QZ-2.1)+0.23
172 Q4=SIN(6.283*TB/TS-1.571)+1.0
    Q5=SIN(12.566*TB/TS-1.571)+1.0
    IF(H)173,173,174
173 AB=0.785*DD*DD
    GO TO 175
174 AB=H*DD
175 W2=PX*BN*SB*RM*1.246/(AB*1000.)
    W3=(Q2/(2.0*VS+(VG/Q4)))**2.0*V1
    W5=(Q3/(2.0*VS+(VG/Q5)))**2.0*V2
    WD=(TS*BG*Q1*CC)**2.0*W2*(W3+W5)
    M=M+1
    IF(M-1)176,176,177
```

```
176 WU=WD
177 GO TO 150
178 G(1)=0
    G(2)=1
    PW=PU
    WW=WU
    DO 183 M=1,2
    UA=G(M)
    PS(M)=PW*UA*UA
    X=WF+WQ
    GM=(GF*UA)**2.+1.
    ST(M)=(2.0*(0.0027*XDPU*UA)**1.8+1.0)*WT
    VA(M)=VV*UA
    DL(M)=GM *WW
    PP(M)=GM*WN
    EX(M)=EZ*PS(M)
    SP(M)=PP(M)+DL(M)+PS(M)+EX(M)+ST(M)+X
    P(M)=(SP(M)/1000.)+VA(M)
    IF(GM)185,184,185
184 PM(M)=0
    E(M)=0
    GO TO 186
185 PM(M)=(SP(M)/P(M))*.1
    E(M)=100.-PM(M)
186 WW=WD
183 PW=PV
    PRINT3,WF,WF
    PRINT3,ST(1),ST(2)
    PRINT3,WQ,WQ
```

```
      PRINT3,PP(1),PP(2)
      PRINT3,DL(1),DL(2)
      PRINT3,PS(1),PS(2)
      PRINT3,EX(1),EX(2)
      PRINT3,SP(1),SP(2)
      PRINT3,VA(1),VA(2)
      PRINT3,P(1),P(2)
      PRINT3,PM(1),PM(2)
      PRINT3,E(1),E(2)
      PRINT321,ENL
      PRINT4,EL(1),EL(2),EL(3),EL(4),EL(5),EL(6)
    4 FORMAT(9X,F12.5)
  321 FORMAT (/9X F12.5)
      PAUSE
      END
```

DERIVATIONS

SECTION SA

POLE-FACE LOSSES IN SOLID POLE GENERATORS

IN BRIEF

Pole-face losses in solid rotor generators can limit the rotational speed, the output, or both. The following article discusses the calculation of, and the design limits imposed by the pole face losses.

GENERAL STATEMENT

Paradoxically, the solid rotor machine is proposed for high speeds and high air-gap flux densities when it cannot operate at speeds or loadings comparable to those of the laminated pole generators, without the penalty of high losses in the solid pole faces.

A solid-pole Lundell generator that operates over a speed range of two to one may require de-rating at the maximum speed because of pole-face losses. This de-rating is required because of the pole face losses under load - not the no load losses.

When the wide speed range generator operates at its maximum speed, the gap density is reduced and the reduction of losses due to the reduced flux density is greater than the loss increase due to the increase in tooth ripple frequency. The result at no load is a reduction in pole face losses. At full load though, the same stator current flows and the armature mmf is the same as it was at the lower speed.

Because of the doubled slot frequency, the pole face load losses at the top speed will be of the order of 3 times as great as at the 1/2 speed condition. The actual increase in pole face losses under load depends upon the slot opening, air gap length, ampere loading, and gap density.

SOURCE OF THE FORMULAE

T. Spooner and I. F. Kinnard "Surface Iron Losses with Reference to Laminated

Materials" Trans. AIEE, Vol. 43, 1924, pp 262-281.

The above reference points out that the following factors influence pole face losses:

1. Air gap induction Bg
2. Field form C.
3. Ratio of slot width to single air gap $\frac{b_s}{g}$
4. Tooth frequency f_t

*5. Tooth pitch τ_s or slot pitch

6. Resistivity of material (ρ)
7. Thickness of individual laminations t
8. Hysteresis Coefficient γ
9. Insulation between laminations
10. Effect of punching

* We use different symbol than Spooner and Kinnard

In the equation -

Pole face losses = $W_S = K_1 K_2 K_3 K_4 K_5 K_6$ (Bore area), the hysteresis coefficient is not used, the interlamination resistance is assumed high, no burrs are assumed to be shorting the laminations and the effect of work-hardening is assumed to be removed by annealing.

In the paper, Spooner and Kinnard summarize that as a rough approximation, surface losses vary as:

$$(Bg)^2, \ (f_t)^{1.5}, \ \frac{b_s}{g}^{1 \text{ to } 2} \quad (\tau_s)^1$$

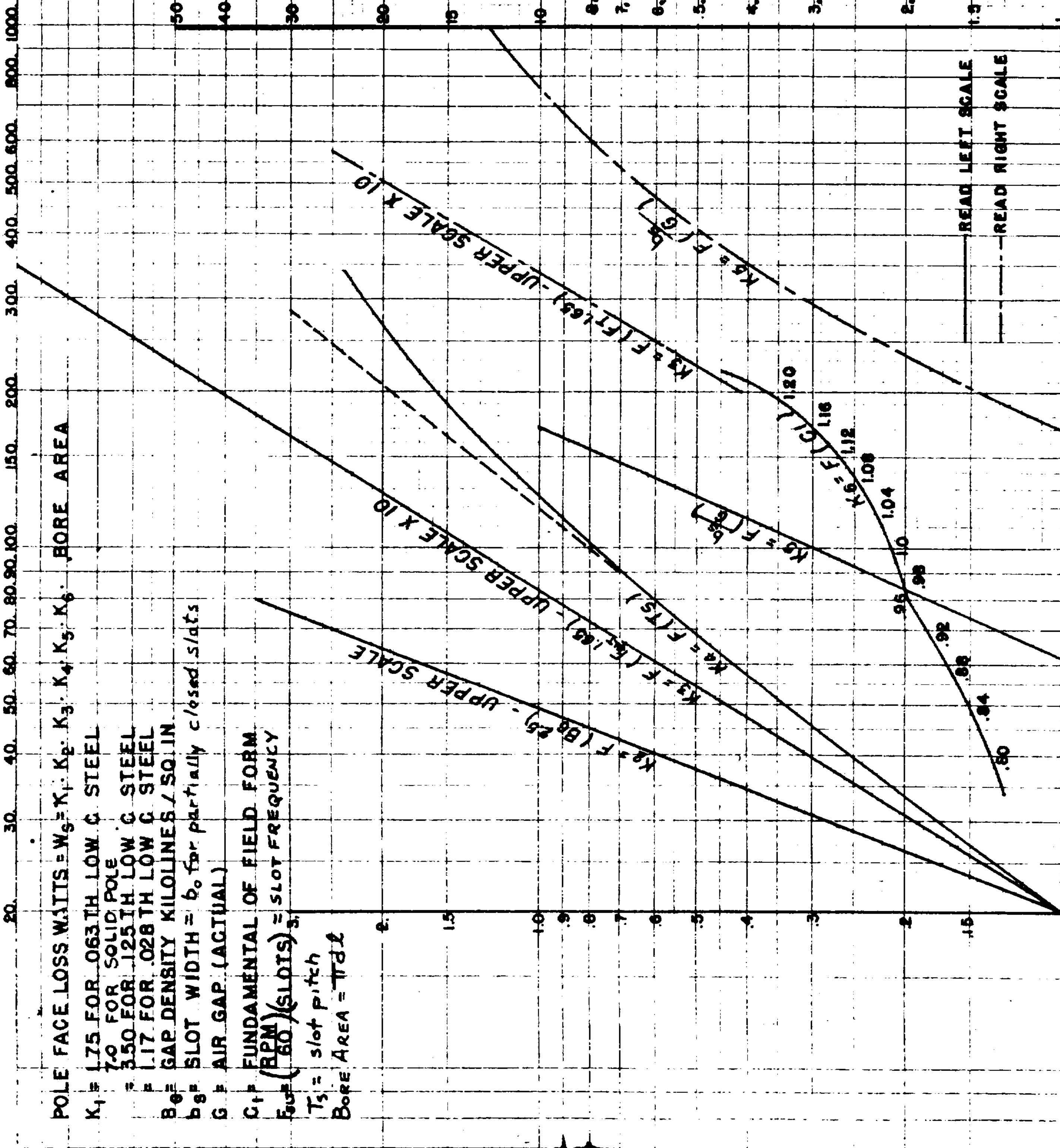
In the text of the paper, higher exponents are used and the constant K_1 is adjusted to give the required accuracy. The exponents used in the curves given in the design manuals of this report are about 30% higher than the rough approximation given by Spooner and Kinnard, and account for interlaminated currents caused by imperfect insulation.

CURVE 2

From Kennard and Spooner "Surface Iron Losses with Respect to Laminated Materials", Trans. AIEE, Vol. 43, 1924, pp 262-281.

DRAWN BY J.A.T.

REFER TO ITEM (186) IN SALIENT POLE DESIGN MANUAL FOR SAMPLE USE OF THIS CURVE



SOLID-POLE P.F. LOSSES

For this study, tests were made on solid-pole generators using 4130 pole steel. Tests correlated within 5% of calculated losses when the constant $K_1 = 7.0$ was used. Load losses in the pole face are calculated just as for laminated poles.

Note: If the rotor is not relieved at the leading and trailing edges of the pole, the losses will be higher than those calculated with $K_1 = 7.0$. Such a condition might exist when 316 steel or Inconel X is welded between poles and the weldment is cylindrical. In such cases, the armature reaction flux causes high losses in the interpolar area. This discussion and calculation assumes that best conditions exist.

NO-LOAD POLE FACE LOSSES

The pole face losses are a function of the stator bore area, and when the stator tooth pitch is constant, the losses are a function of the rotor diameter. They are also functions of the gap density and under load they are functions of the stator loading. Since the RPM determines the tooth ripple frequency, the P.F. losses are a function of the RPM.

The flux density and speed of a specific, solid pole generator, are limited by the amount of heat that can be dissipated from the surface of the poles so without considering the output of the generator, the effect of slot pitch and air gap density on pole face losses can be observed, while the generator operates at no-load.

With a specified air gap density and specified slot pitch, the pole face losses can be made high enough to cause the machine to fail and this can happen without load being applied. It can happen to a laminated pole or to a solid pole generator.

The no load pole face losses in a solid pole generator are of the order of six (6) times as great, for the same stator design, as those in the pole faces of a laminated rotor. For this reason only the design limits for the solid pole generators are investigated here.

No load pole face losses are = fn (Bg, $\frac{b_s}{g}$, f_T, τ_s, C_1) where

Bg = air gap density, Kilolines/in^2

b_s = slot opening, inches

g = air gap length, inches

f_t = tooth ripple, cycles/sec

τ_s = tooth pitch on stator, inches

C_1 = fundamental of field form (a ratio)

For most of the following discussion, the following values are assumed fixed:

$$\frac{b_s}{g} = 2.0$$

$$\tau_s = .3''$$

$$C_1 = 1.0$$

Since τ_s = .3, now the number of teeth is a function of d.

$$\text{No. Teeth} = \frac{\pi d}{.3}$$

$$f_t = \frac{\pi d}{.3} \cdot \frac{\text{RPM}}{60}$$

PFL at NL = $K_1\ K_2\ K_3\ K_4\ K_5\ K_6$ (Bore Area)

K_1 = 7.0

K_2 = fn (B_g) = .8 for 45 Kilolines/in^2 gap density

$$K_3 = \text{fn}\,(f_T)^{1.65} = \text{fn}\left[\frac{\pi d}{.3}\ \frac{(RPM)}{60}\right]^{1.65}$$

$$K_4 = \text{fn}\,(\tau_s) = .175$$

$$K_5 = \text{fn}\,\left(\frac{b_s}{g}\right) = 1.45$$

$$K_6 = \text{fn}\,(C_1) = .22$$

PFL at NL = (7.0) .8 (K_3) (.175) 1.45 (.22) (Bore Area)

= .313 K_3 (Area) for Bg = 45 Kilolines/in^2

= .235 K_3 (Area) for Bg = 40 Kilolines/in^2

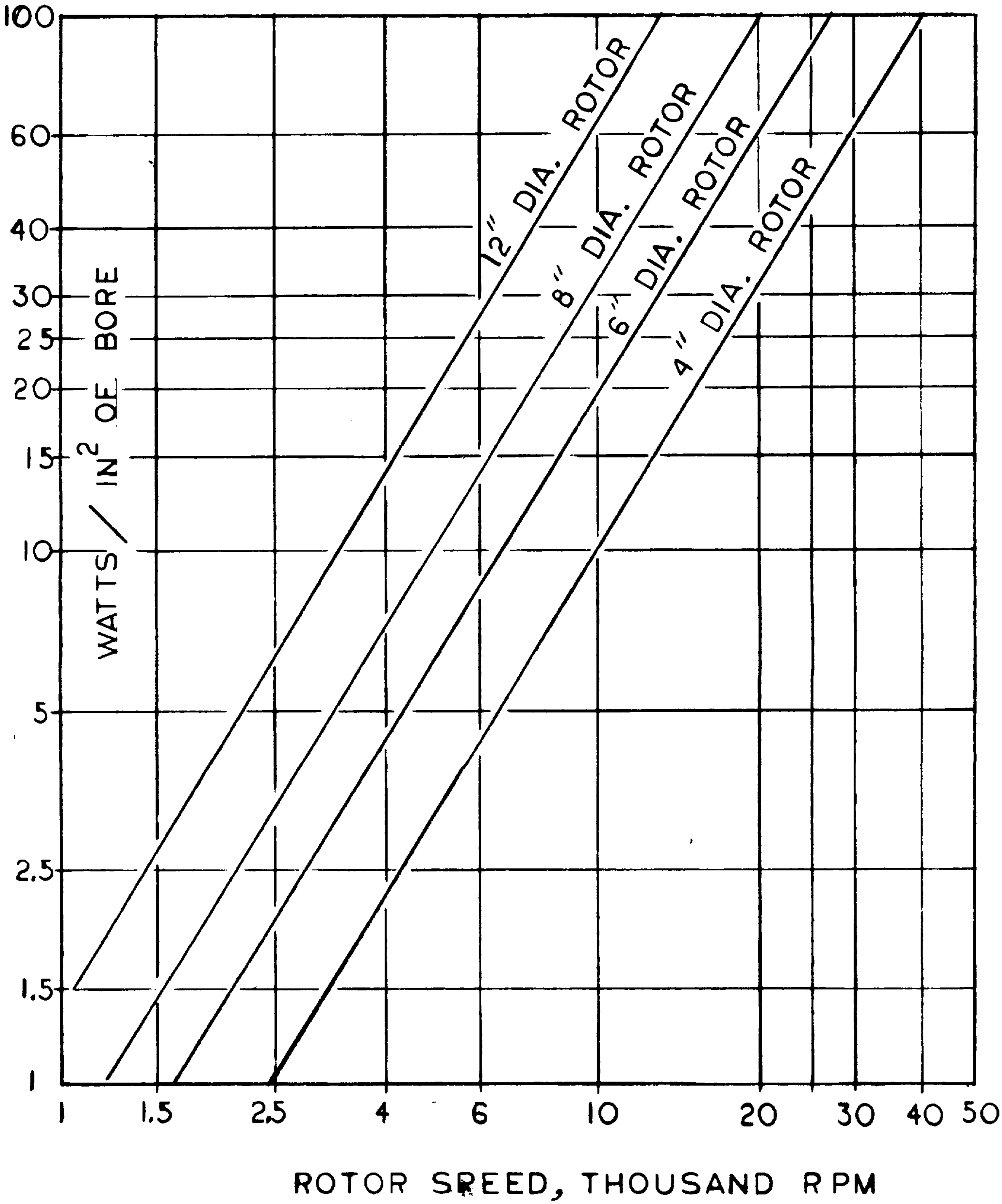
= .11 K_3 (Area) for Bg = 30 Kilolines/in^2

= .039 K_3 (Area) for Bg = 20 Kilolines/in^2

Rotor Dia. In.	RPM	No-Load Pole Face Loss in Watt/in^2 τ_s = .3			
		Bg = 45	Bg = 40	Bg = 30	Bg = 20
4	2,000	.72	.54	.25	.09
"	4,000	2.28	1.7	.8	.284
"	8,000	7.2	5.4	2.5	.9
"	12,000	14.1	10.6	4.9	1.76
"	24,000	44	33	15.4	5.5
"	48,000	128	96	45	16
6	2,000	1.4	1.05	.49	.17
"	4,000	4.4	3.3	1.54	.55
"	8,000	14	10.5	4.9	1.75
"	12,000	27	20.2	9.5	3.37
"	24,000	86	64.5	30	10.7
"	48,000	272	204	95	34

POLEFACE LOSSES IN A SOLID POLEFACE AT NO LOAD AS A FUNCTION OF SPEED WHEN THE GAP DENSITY $B_g = 45\ KL/_{IN^2}$

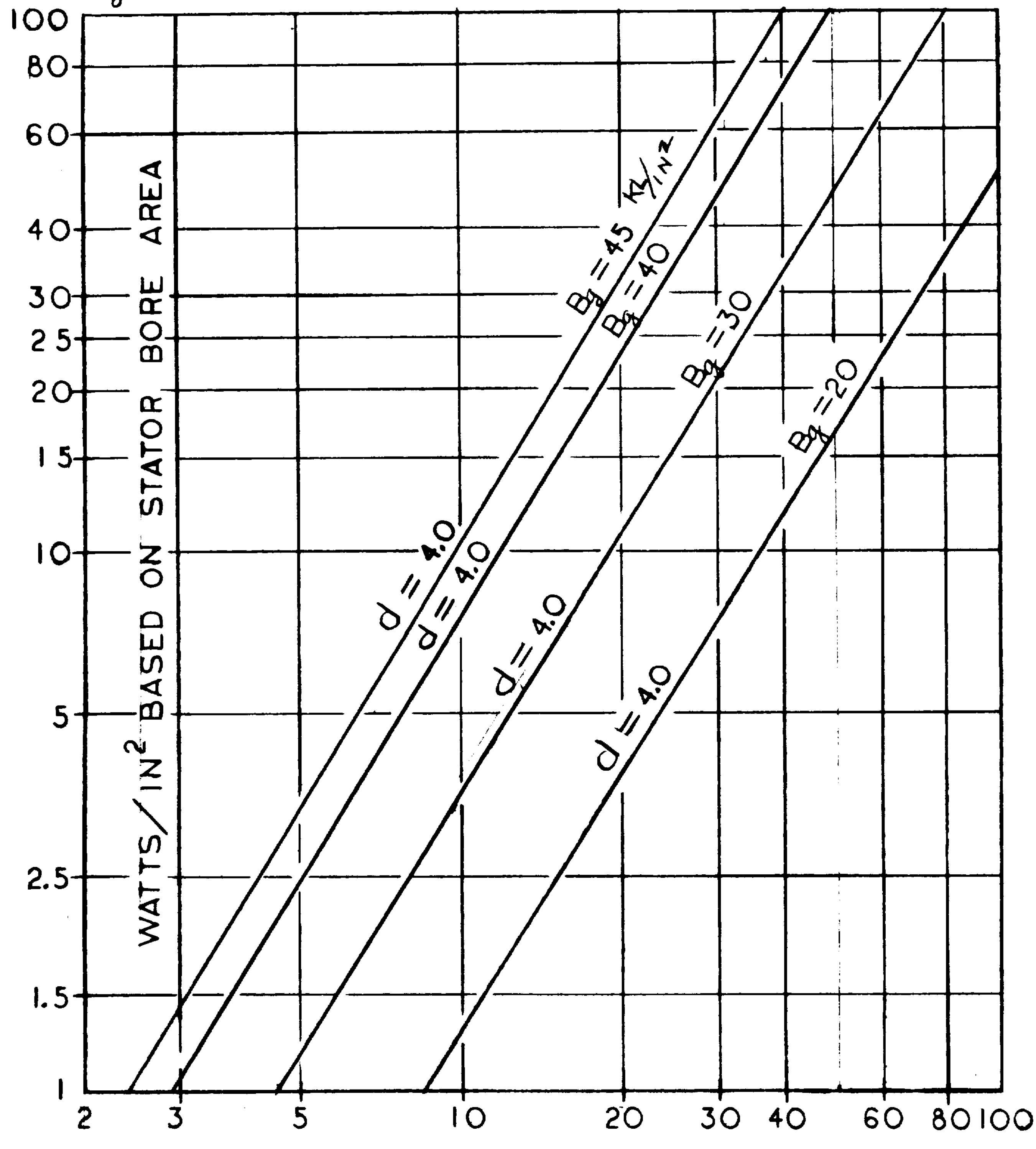
$b_s/g = 2.0$ SLOT PITCH $\tau_s = .30$



CURVE SA-1

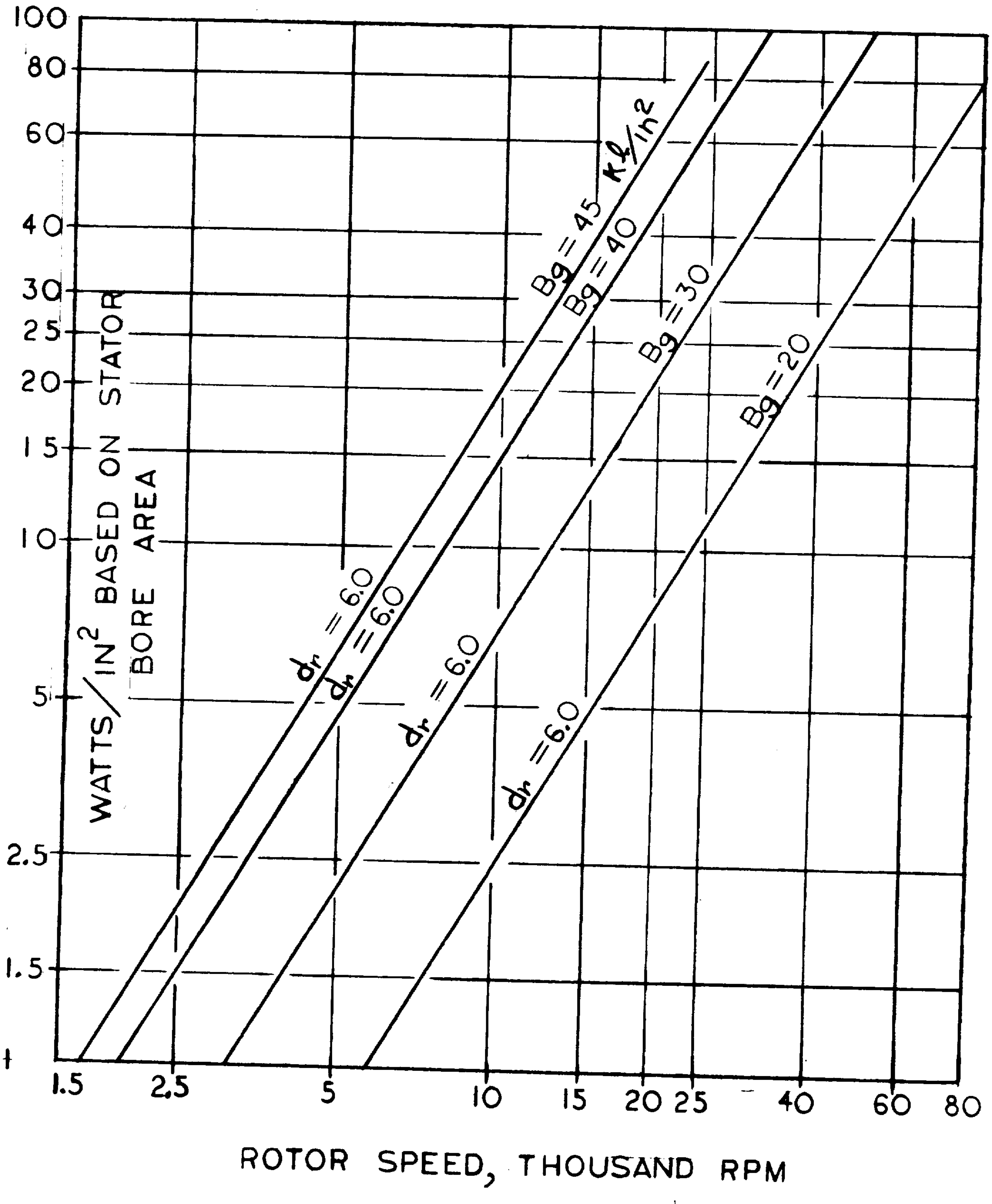
POLE FACE LOSSES IN A SOLID POLE FACE AT NO LOAD AS A FUNCTION OF SPEED AND AIR GAP DENSITY FOR A 4.0 DIA. ROTOR.

$\frac{b_s}{g} = 2.0$ SLOT PITCH $= \tau_s = .30$



CURVE SA-2

POLEFACE LOSSES IN A SOLID POLEFACE AT NO LOAD AS A FUNCTION OF SPEED AND AIR-GAP DENSITY FOR A 6.0" DIA. ROTOR. $b_s/g = 2.0$ SLOT PITCH, $\tau_s = .30$



CURVE SA-3

DISSIPATING THE POLE FACE LOSSES

If the pole face losses are to be dissipated to gas similar to air or if the machine is force ventilated with air, the best coefficient that could be expected is 0.10 watts/in^2 of surface/^{o}C rise above the air. See curve SA4 from Luke and curve SA5 from A.D. Moore.

If 25 watts/in^2 is to be dissipated from the rotor surface, the temperature rise of the rotor surface in this case will be $\frac{25}{.10} = 250^oC$ above the cooling air or gas. Similarly, if 50 watts/in^2 must be dissipated, then the temperature rise of the rotor will be 500^{o}C above the cooling air.

If room temperature cooling air can be used in sufficient quantity, 40 watts/in^2 might possibly be dissipated from the generator rotor surface. If a heat transfer coefficient of .10 w/in^2/^{o}C can be obtained, the rotor temperature will be approximately 800^{o}F or 425^{o}C.

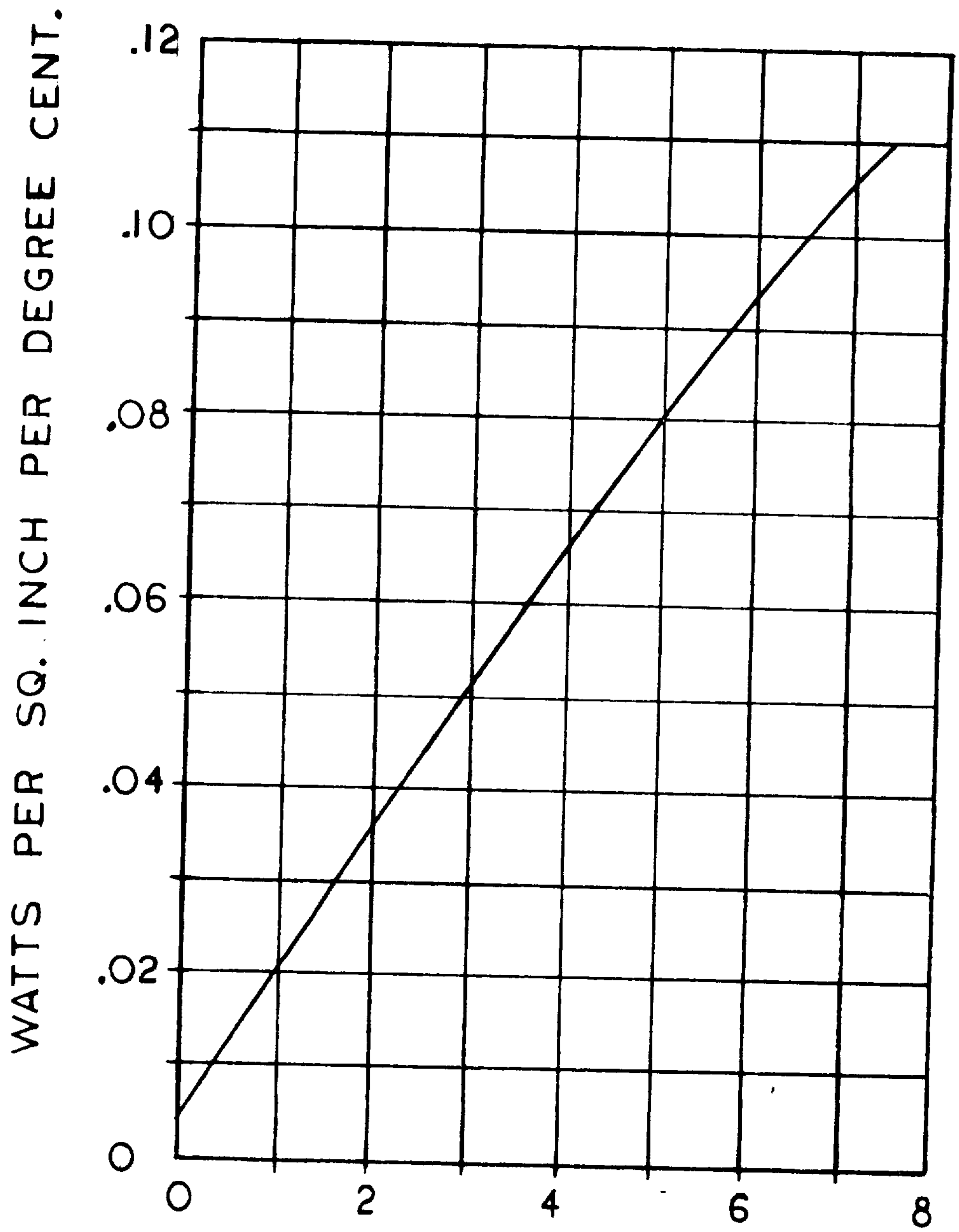
A cooling coefficient more likely to be obtained is .08 watts/in^2/^{o}C and this value has been used on curve SA6 to show probable rotor temperatures associated with various no-load pole face loss levels.

EFFECT OF REDUCING GAP DENSITY

If a high-speed generator is designed and the PF losses are too great at say 45 kilolines/in^2 air gap density, reducing the flux density will reduce the pole-face, no-load losses by the ratio of gap densities raised to the power 2.5. The factor for gap density is K_2.

Bg	K_2
20	.10
25	.18
30	.28
40	.6
45	.8

SURFACE HEAT DISSIPATION FROM A GENERATOR ROTOR.



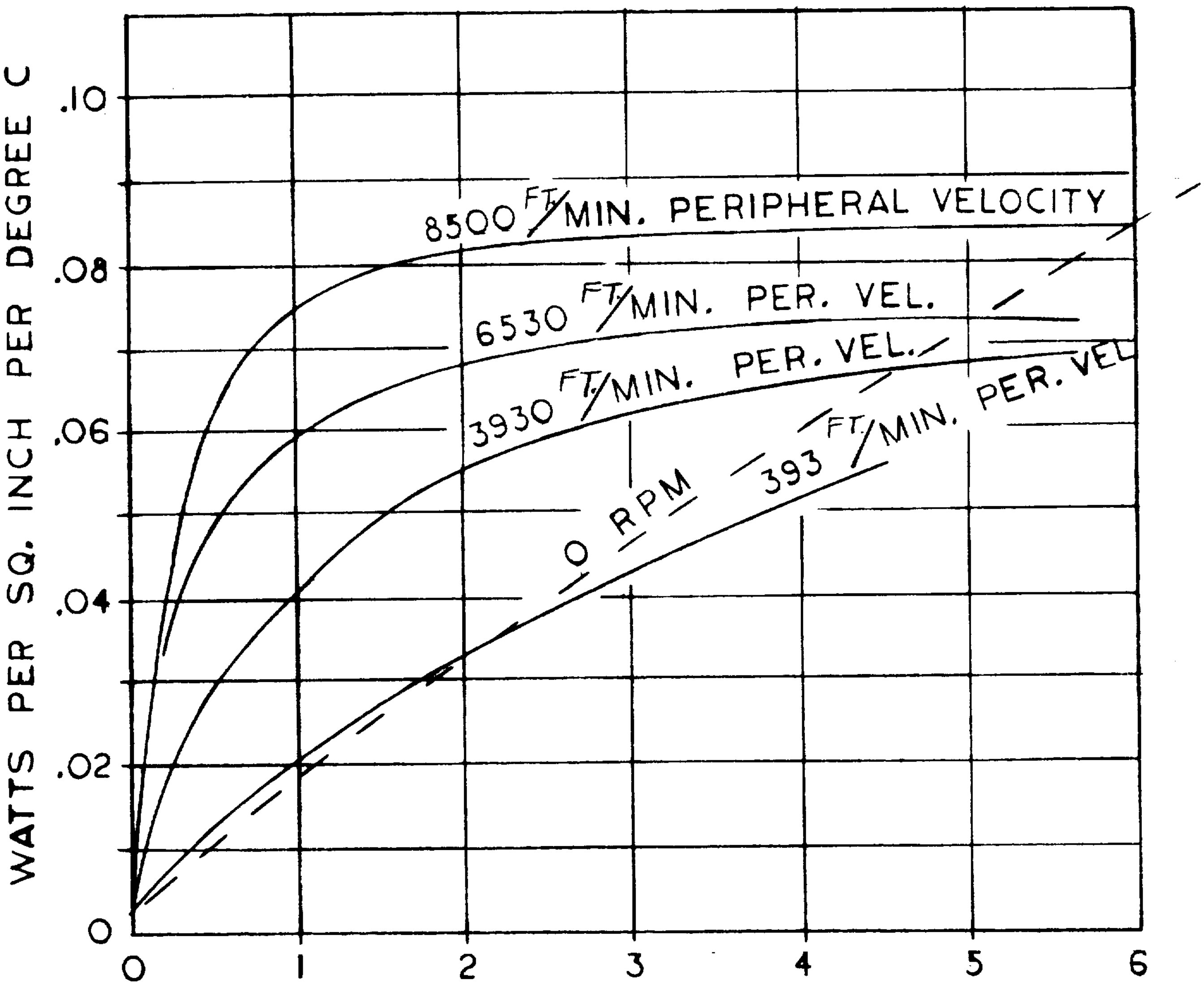
AVERAGE AIR VELOCITY THROUGH MACHINE IN THOUSANDS OF FEET PER MINUTE.

FROM LUKE: HEATING OF RAILWAY MOTORS. AIEE TRANS 1922 VOL 41 PP 165-173.

CURVE SA-4

WATTS DISSIPATED FROM THE ROTOR OF AN ELECTRICAL MACHINE WHEN FORCED-AIR COOLING IS USED.

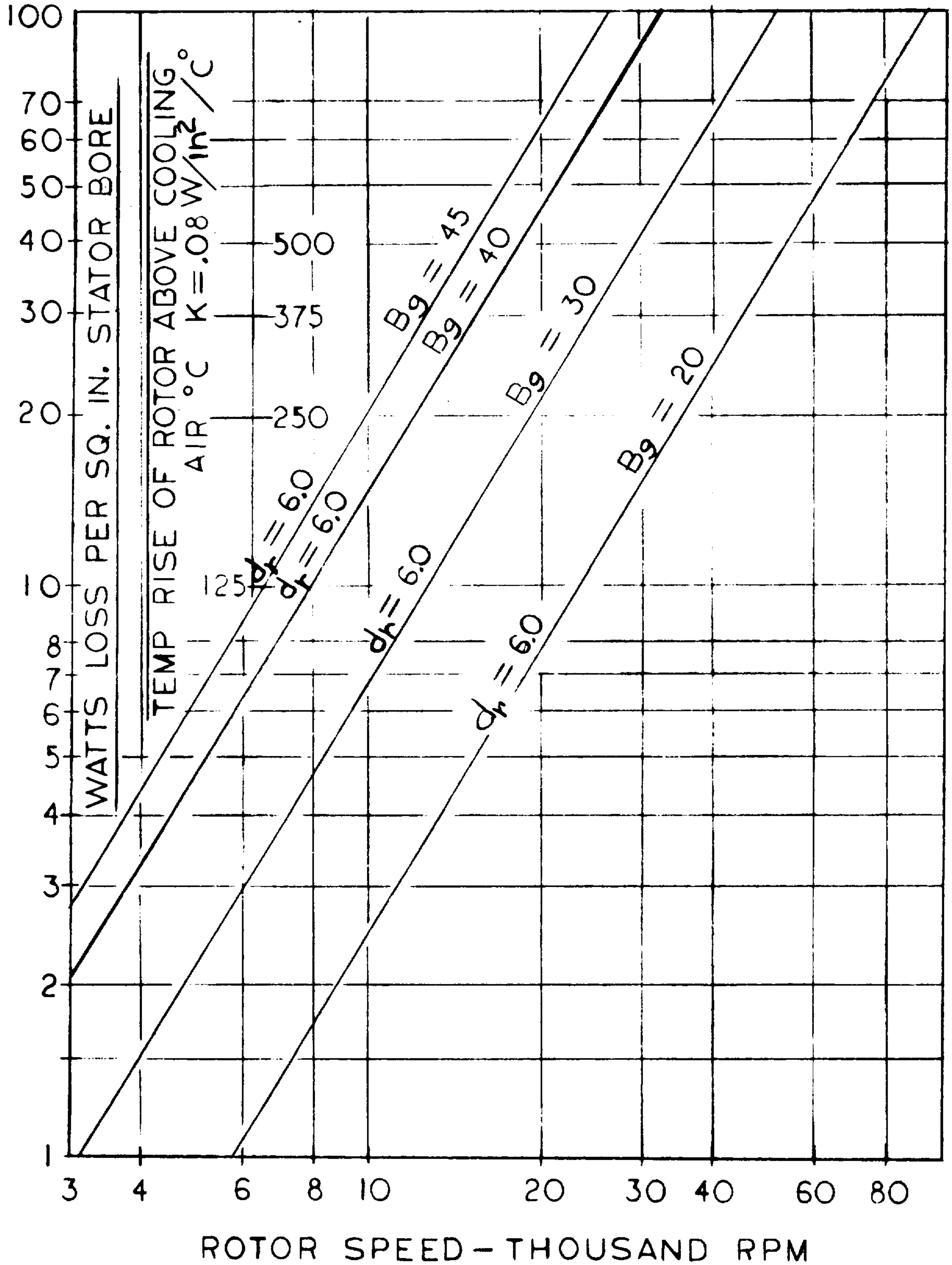
FROM A.D. MOORE: FUNDAMENTALS OF ELECTRICAL DESIGN. McGRAW HILL 1927 PAGE 134.



AVERAGE COOLING AIR VELOCITY THROUGH THE MACHINE AIR-GAP - THOUSANDS OF FEET PER MINUTE.

CURVE SA-5

NO LOAD POLE FACE LOSSES FOR A SOLID-ROTOR GENERATOR HAVING 6.0 DIA. ROTOR AND A TOOTH PITCH OF .3" $b_s/g = 2.0$



CURVE SA-6

EFFECT OF VARYING SLOT PITCH

When the slot pitch is varied, the pole face loss varies as the slot ripple frequency variation raised to the 1.65 power and varies as the tooth pitch variation raised to the 1.26 power. The no-load pole-face loss will decrease as the tooth or slot pitch is increased.

The net change in the loss as the slot pitch increases is approximately (ratio of slots)$^{1.65}$ (ratio of slot pitches)$^{1.26}$.

In the tabulation for diameter = 4.0", Bg = 40 Kl/in^2, τ_s = .3", RPM = 12000, the NLPFL = 10.6 watts/in^2 of stator bore.

If the slot pitch is increased to .6", the NLPFL will be reduced to 8.1 watts/in^2 of stator bore area.

EFFECT OF SLOT OPENING

Completely closing the slots can have only limited effect in reducing pole face losses since the bridge closing the slot must saturate before the machine can operate. The saturated bridge represents an effective opening in the slot and the ratio $\frac{b_s}{g}$ is some definite value. In considering the effect of closing the slot with a bridge, a smaller effective opening can be assumed such as $\frac{b_s}{g}$ = 1.0. The pole face loss at no load varies approximately as the ratio

$$\left(\frac{\frac{b_{s2}}{g}}{\frac{b_{s1}}{g}}\right)^{1.3} = \left(\frac{b_{s2}}{b_{s1}}\right)^{1.3}$$

So, by reducing the slot opening to 1/2 its original width, the no-load losses can be reduced to about 1/2.4 of the initial no-load value. <u>This applies to the no load losses only and the pole-face losses under load may be much higher because of the reduced slot opening</u>. Load losses in the pole-face are a function of the stator loading and of the slot opening to air gap ratio (bs/g). This can be expressed as a function of bs/g and a function of (Xad)^2.

LOAD LOSSES IN THE POLE FACE

Under load, the pole face losses are increased. This increase is due to the armature mmf wave and resulting flux wave which has a saw tooth shape.

The higher the current loading in the stator, the more pronounced the saw tooth shape of the flux wave becomes when the machine is fully loaded. This effect is a function of the ratio -

$$\left[\frac{\text{series conductors/slot x } I_{ph}\, K_{sc}}{\text{no load air gap ampere turns}}\right]^2 \quad \text{(NLPFL)}$$

where K_{sc} is a modifying factor describing the effect of $\frac{b_s}{g}$. The smaller the opening, the sharper the step or saw-tooth in the armature reaction flux wave.

E.I. Pollard treated the pole face load losses in his paper "Load Losses in Salient Pole Synchronous Machines", AIEE Trans., Vol. 54, 1935, pp 1332-1340. His work shows that if the slot opening to air gap ratio is made too small, the result may be an increase in total pole face losses. See curve SA-7.

In the rotor sizes 4.0" dia. to 8.0" dia., an air gap length of .030" is reasonable to assume. If the following values are assumed:

ampere loading = 900 ampere wires per inch of stator bore periphery, $bs/g = 2.0$, $Bg = 40$ Kl/in^2, then the air gap ampere turns are about 400 and from curve

$$\text{PF load losses} = \left[\frac{K_{sc}\, I_{ph}\, N_s}{AGAT}\right]^2 \quad \text{NLPFL}$$

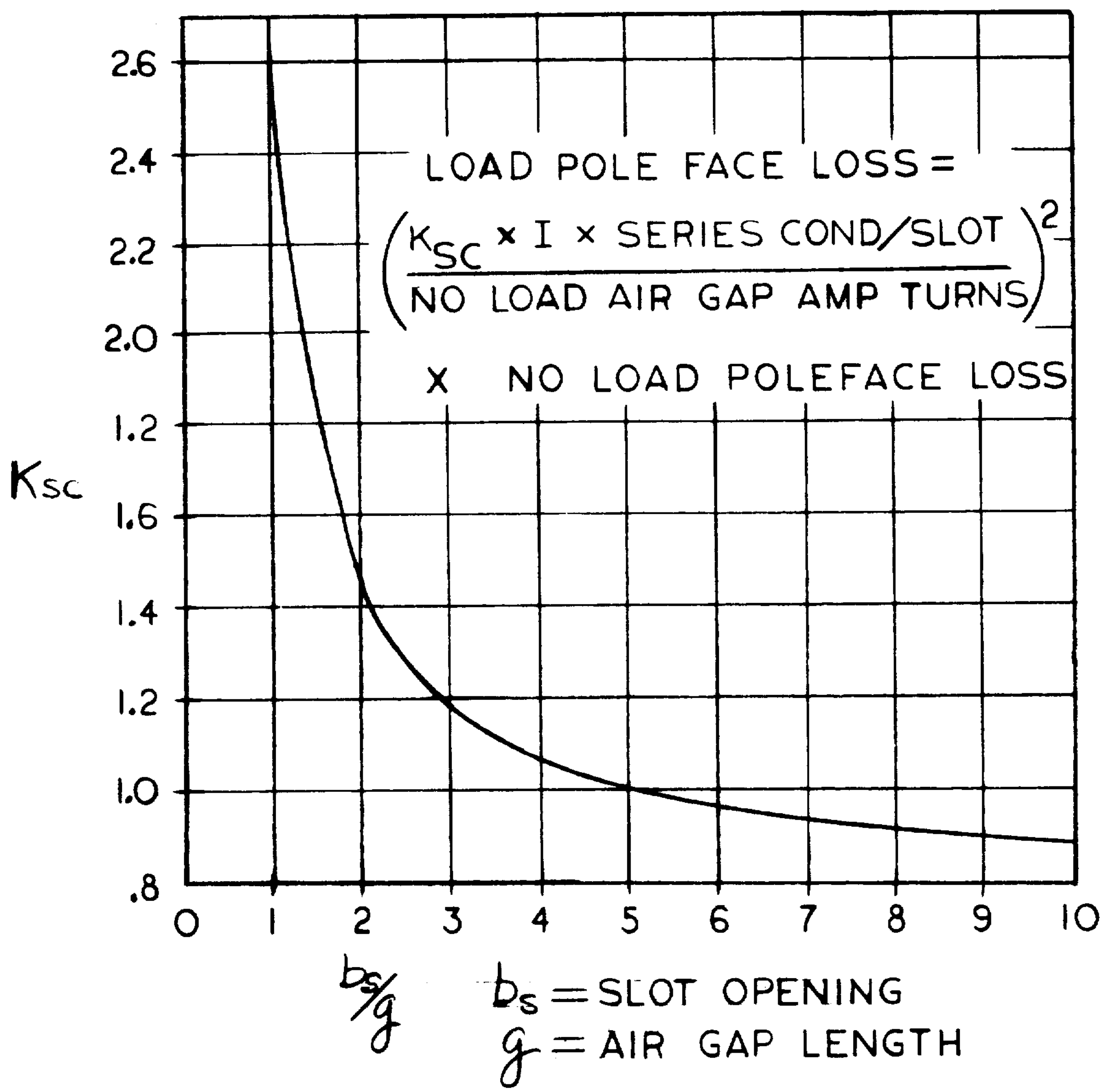
$$= \left[\frac{1.4\,(270)}{400}\right]^2 \quad \text{NLPFL}$$

PF Load Losses = .91 x no load PF losses

where N_s = conductors/slot

$I_{ph}\, N_s$ = 900 x .3 = ampere wire loading x slot pitch

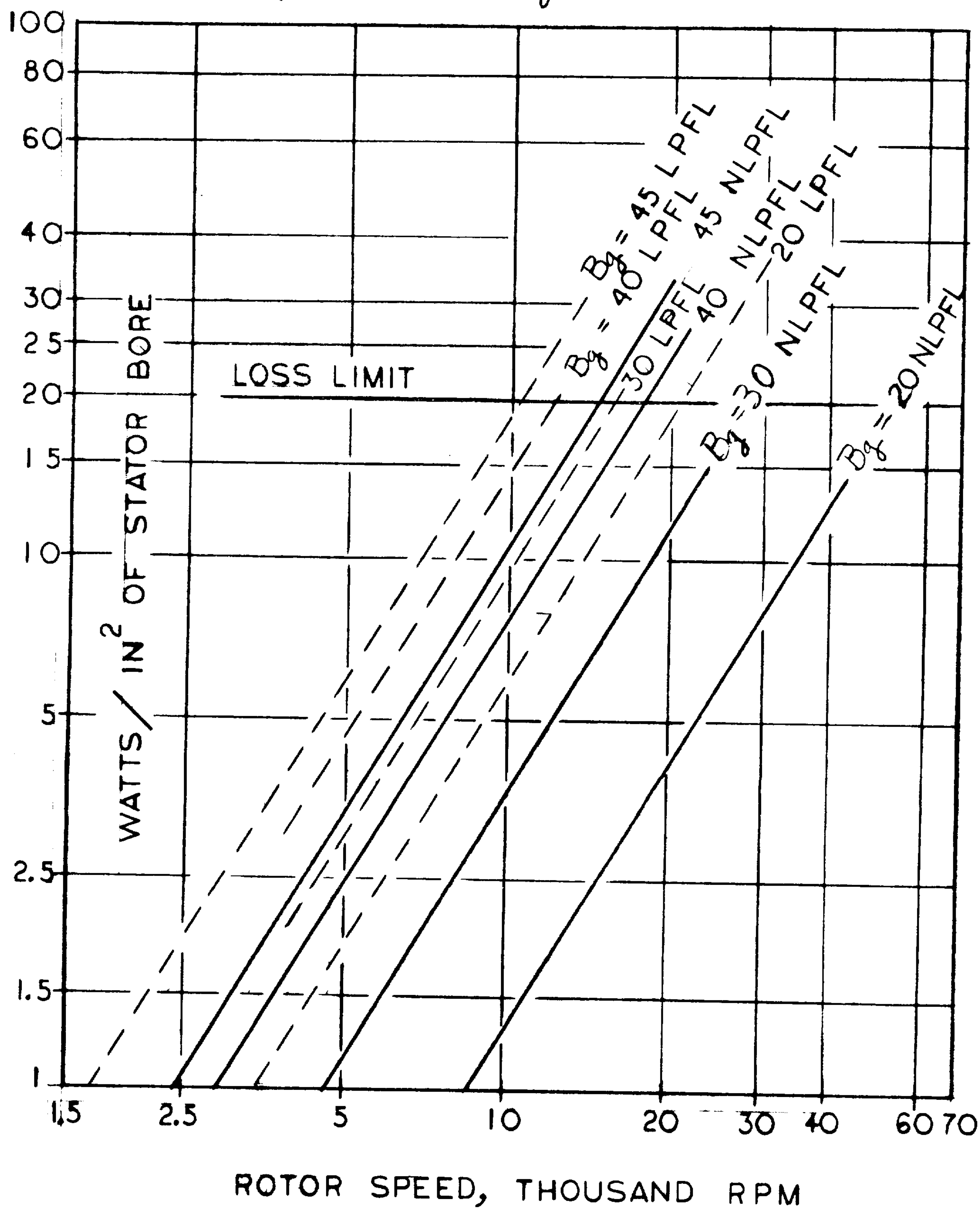
LOAD LOSSES IN THE POLE FACE
FROM E.I. POLLARD: LOAD LOSSES IN SALIENT POLE SYNCHRONOUS MACHINES, AIEE TRANS. VOL. 54 1935 PP 1332 1340.



CURVE SA-7

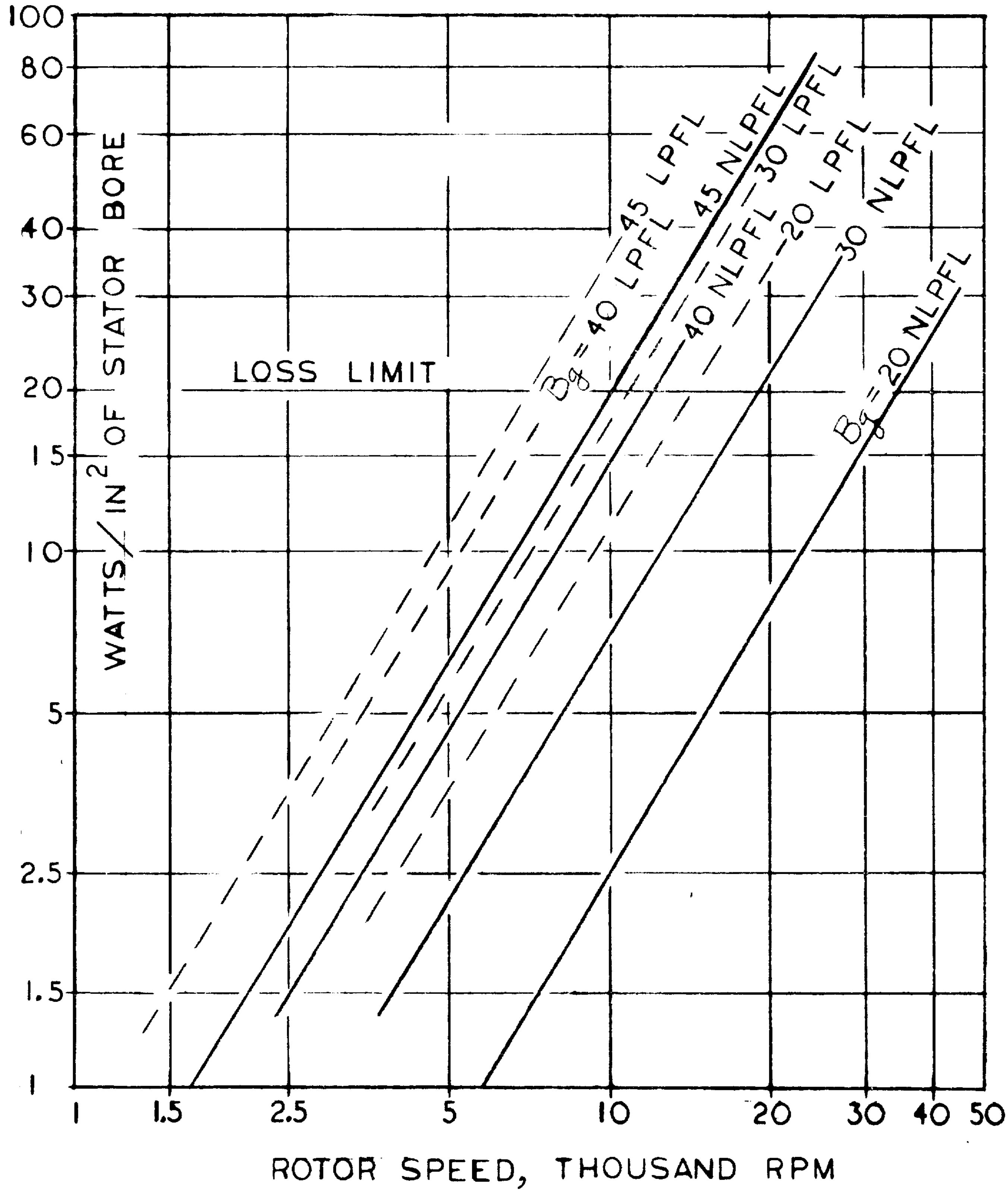
SOLID POLE FACE

POLE FACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 4.0" DIA. ROTOR AT VARIOUS GAP DENSITIES. A=900 $b_s/g = 2.0$ $\tau_s = .3$



CURVE SA-8

POLE FACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 6.0" DIA. ROTOR AT VARIOUS GAP DENSITIES.
A = 900 $b_s/g = 2.0$ $\tau_s = .3$

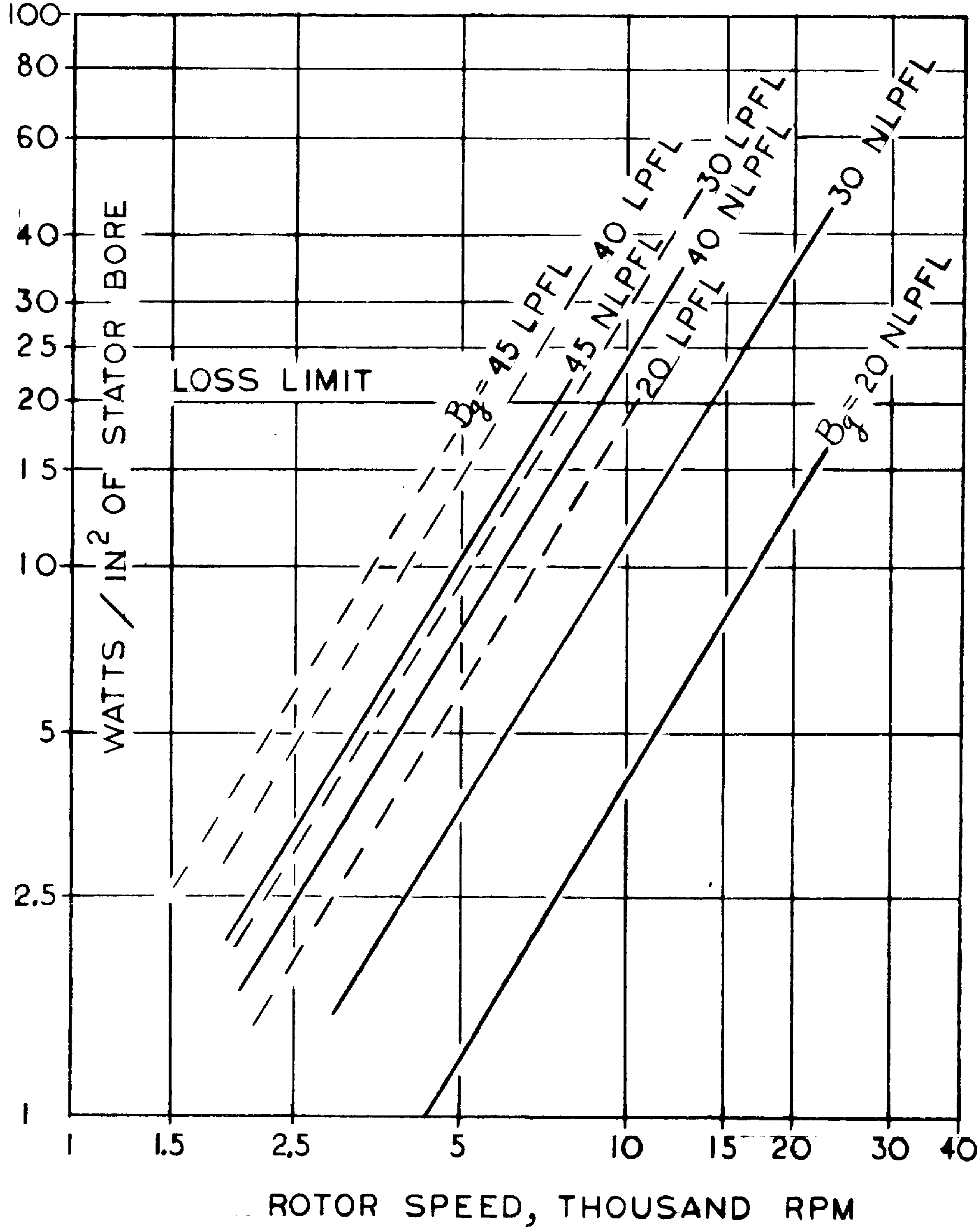


SA-18

CURVE SA-9

POLEFACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 8.0" DIA. ROTOR AT VARIOUS GAP DENSITIES

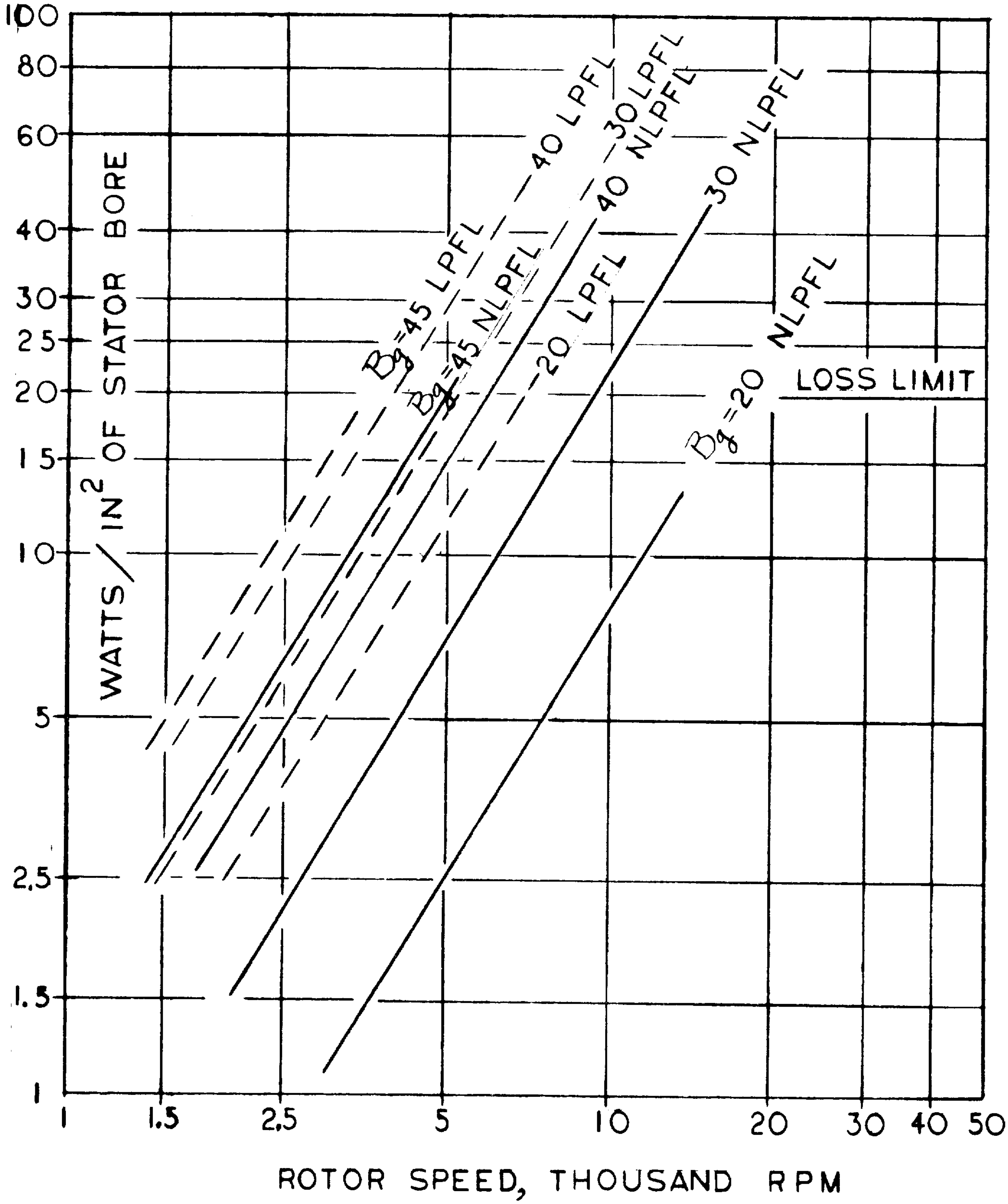
GAP DENSITIES: A=900, $b_s/g = 2.0$, $\tau_s = .30$



CURVE SA-10

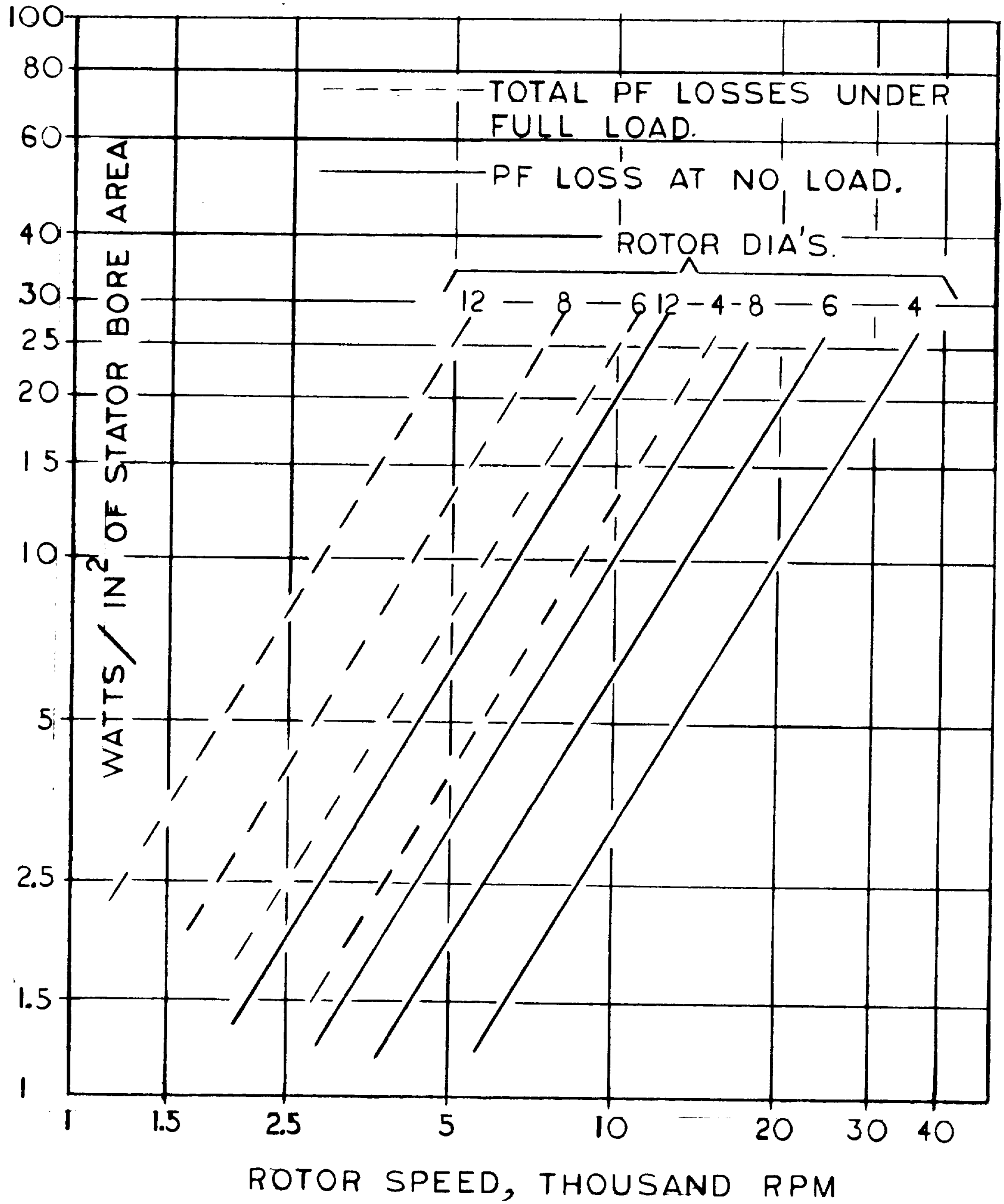
SOLID POLE FACE

POLE FACE LOSSES AT NO LOAD AND AT FULL LOAD FOR 12.0" DIA. ROTOR AT VARIOUS GAP DENSITIES. A=900 $b_s/g = 2.0$ $\tau_s = .30$



CURVE SA-11

POLEFACE LOSSES AT NO LOAD AND AT FULL LOAD FOR ROTORS OF VARIOUS DIAMETERS $B_g = 30\ KL/IN^2$
$A = 900\ AW/IN$ SLOT PITCH = .4 $b_s/g = 20$

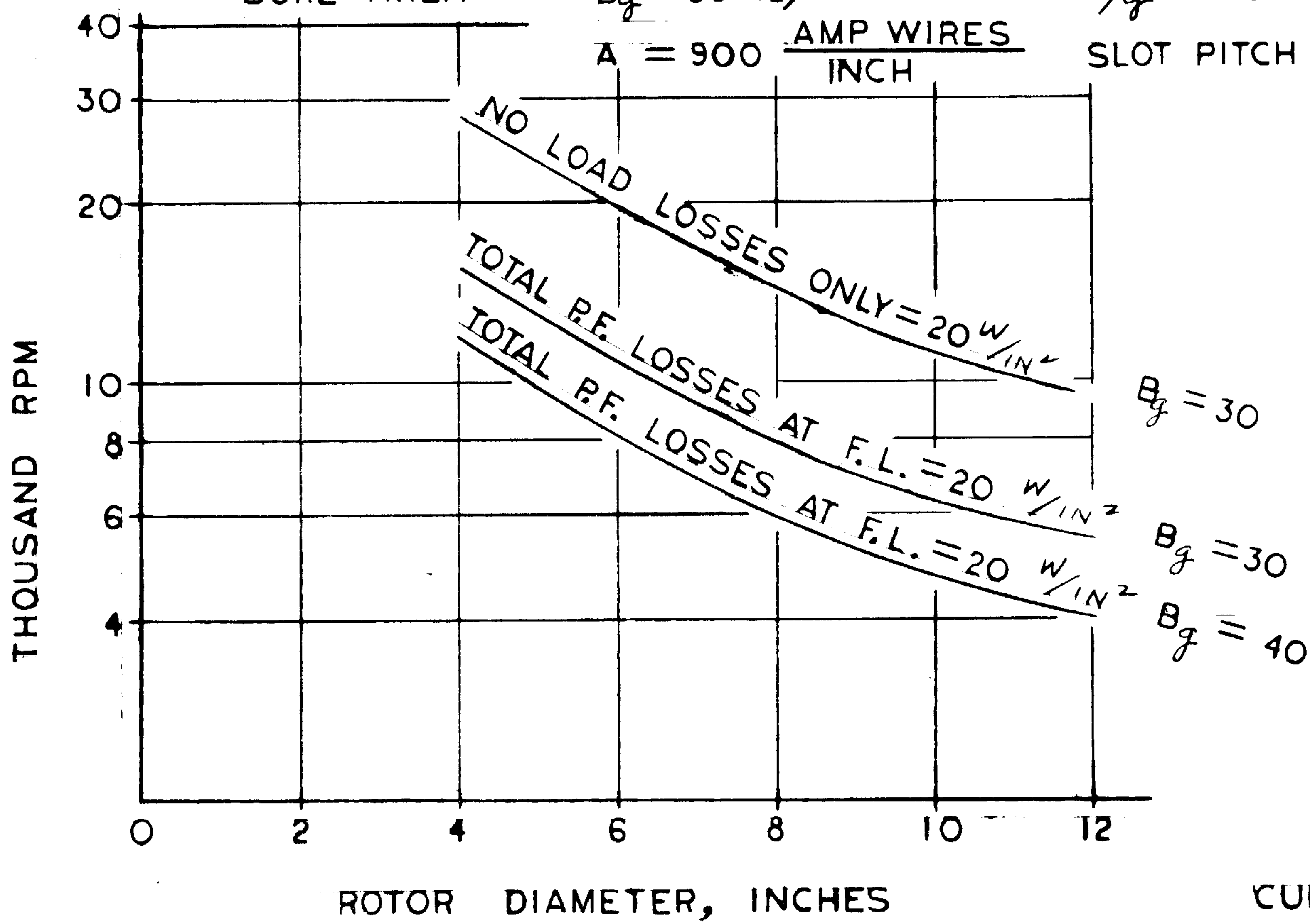


CURVE SA-12

ROTOR DIA. VS ROTOR SPEED FOR SOLID POLE FACE ALTERNATORS LIMITED TO 20 WATTS / IN^2 POLE FACE LOSSES BASED ON STATOR BORE AREA

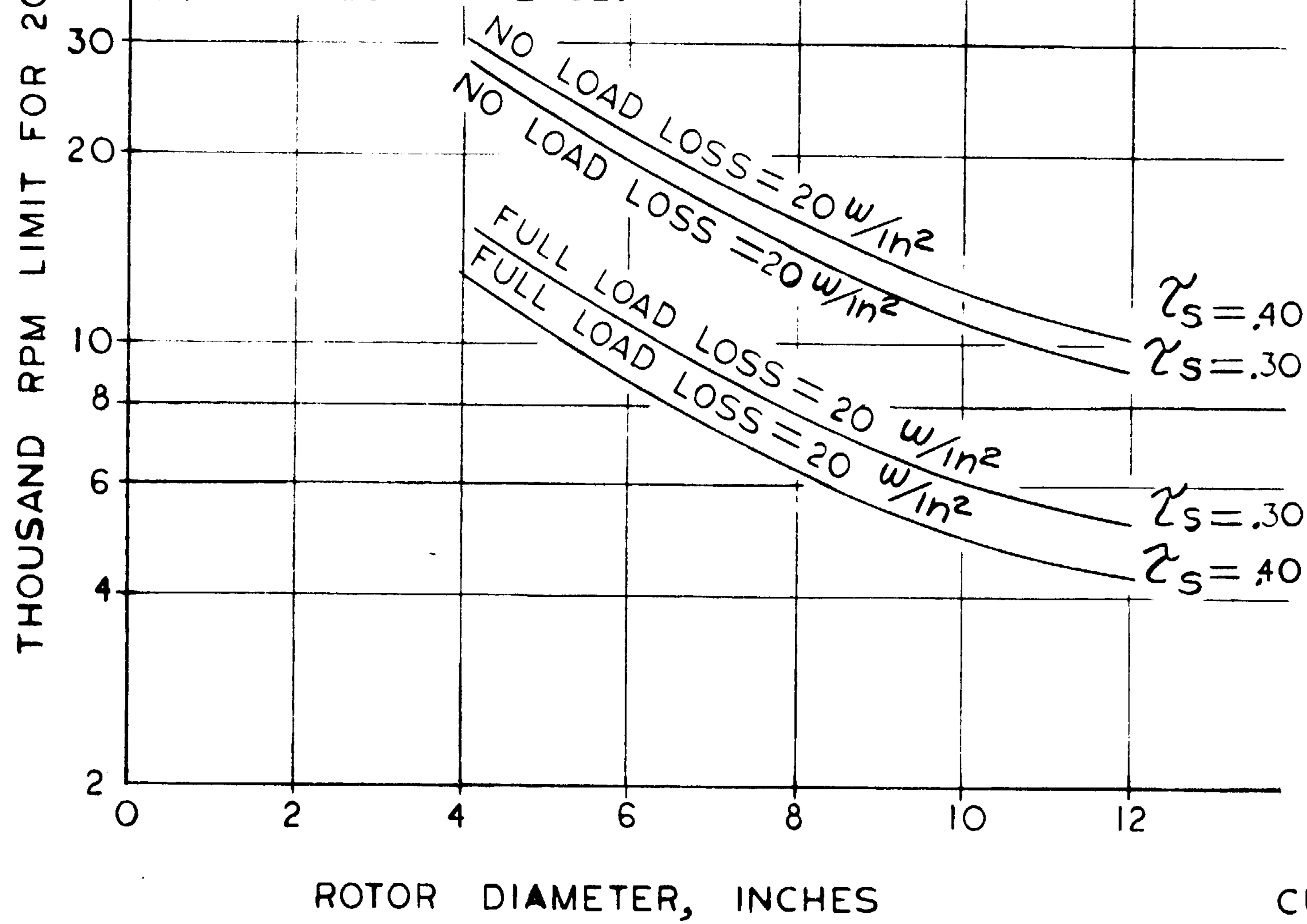
$B_g = 30\ KL/IN^2$ $\qquad b_s/g = 2.0 \qquad C_1 = 1.0$

$A = 900\ \frac{\text{AMP WIRES}}{\text{INCH}}$ $\qquad$ SLOT PITCH = .30



CURVE SA-17

ROTOR DIA. VS ROTOR SPEED FOR SOLID POLE FACE ALTERNATORS LIMITED TO 20 WATTS PER SQ. INCH BASED ON THE STATOR BORE AREA. A COMPARISON OF LOSSES WHEN ONLY THE SLOT PITCH IS CHANGED. NOTE THAT WHEN THE SLOT PITCH IS INCREASED THE NO-LOAD LOSSES ARE REDUCED BUT UNDER LOAD THE TOTAL PF LOSSES INCREASE.



CURVE SA-14

$AGAT = 400 =$ ampere turns drop across main air gap

K_{sc} = loss factor from curve

The pole-face load losses are added to the no-load pole-face losses.

When the air gap density is decreased, the ampere turns drop across the air gap decreased in direct proportion and the pole-face load losses increase as the square of the change in gap density. For example, the factor just calculated above for a 40 Kl/in^2 gap density was .91 (NLPFL). When the gap density in the same machine is reduced to 30 Kl/in^2 but the ampere loading is maintained at 900 AW/in^2, the loss eqn. becomes -

$$PFLL = \left[\frac{1.42\ (270)}{300}\right]^2 \quad NLPFL = 1.63\ (NLPFL)$$

$$\text{or } PFLL = \left(\frac{4}{3}\right)^2 \quad (.91)\ NLPFL = 1.63\ (NLPFL)$$

We have already discussed how the reduction of the air gap flux density reduces the pole face no load loss per square inch of stator bore area by $\left(\frac{B_{g2}}{B_{g1}}\right)^{2.5}$ and in the case of a reduction from 40 Kl/in^2 to 30 Kl/in^2 the reduction in NLPFL is $\left(\frac{3}{4}\right)^{2.5} = .488$.

The full load PFL increased by $\left(\frac{4}{3}\right)^2$ or 1.78 so the total load loss was reduced from 1.0 to 1.78 (.488) = .87 a reduction of 13%.

SLOTTING THE ROTOR TO REDUCE THE POLE-FACE LOSSES

Figure 1 shows graphically what happens when a solid pole-face is slotted to reduce pole face losses, when the slot approximates 50% of the pole surface.

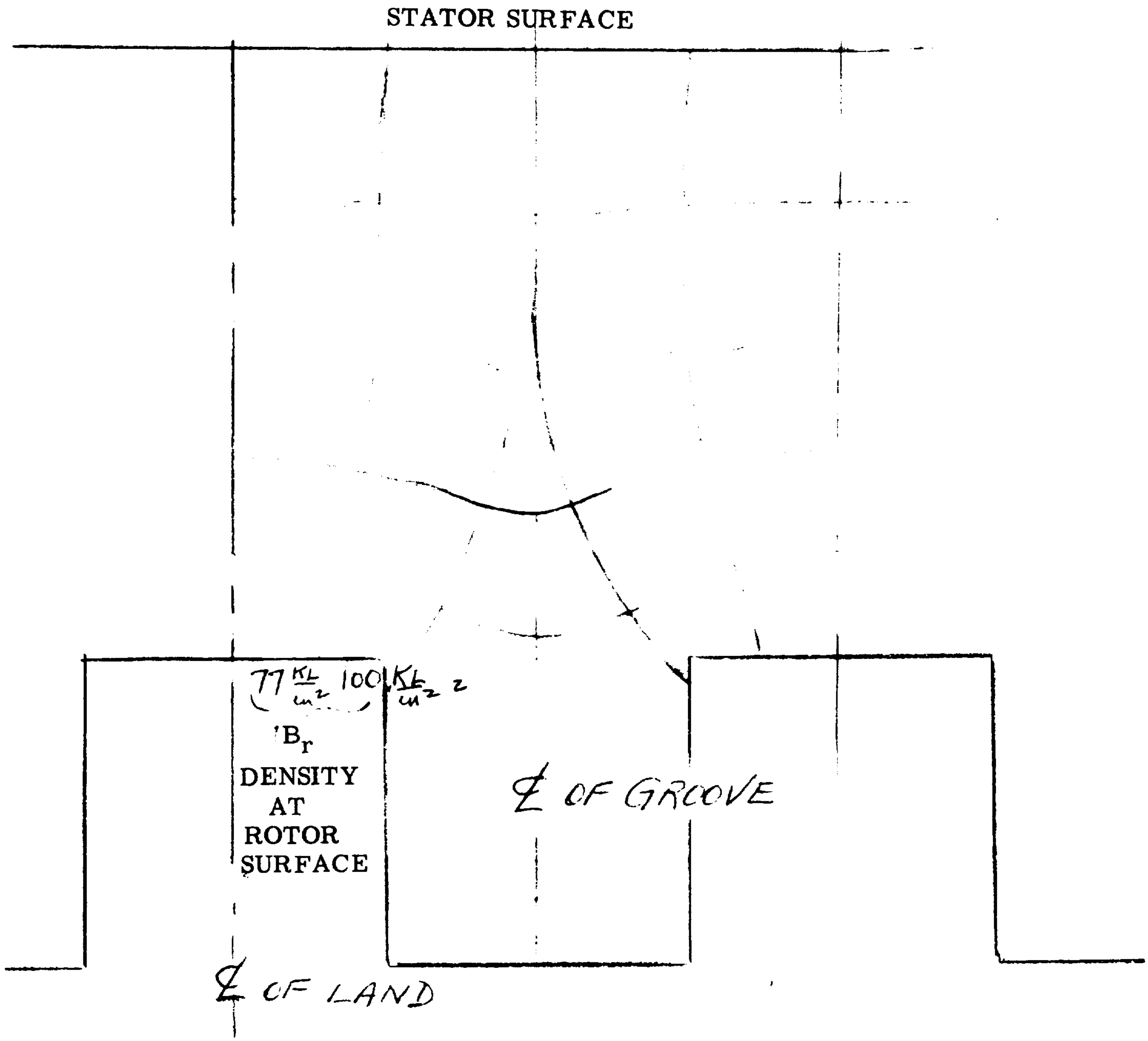
Assuming that the air gap flux density is unity, the initial pole face density at its surface was also unity.

When the rotor was slotted to the extent that 50% of the surface was removed, the density in 1/2 the remaining surface or 1/4 of the initial surface became 1.74 times the initial value or 1.74 per unit. The surface density in the remaining 1/4 of the initial surface increased to 2 times the surface density or 2.0 per unit. The average increase in total pole face losses based upon the increase in gap density at the surface of the pole is 2.4 times. However, the increased air gap density in the region of the pole surface reduces the effect of the slot ripple and tends to reduce the load losses. These effects can nearly enough offset the effect of grooving to make the pole face losses about the same with or without grooving.

Experiments made in support of this study showed insignificant results when the rotor was grooved approximately with .020-.03 wide grooves, and only 50% of the initial surface was left.

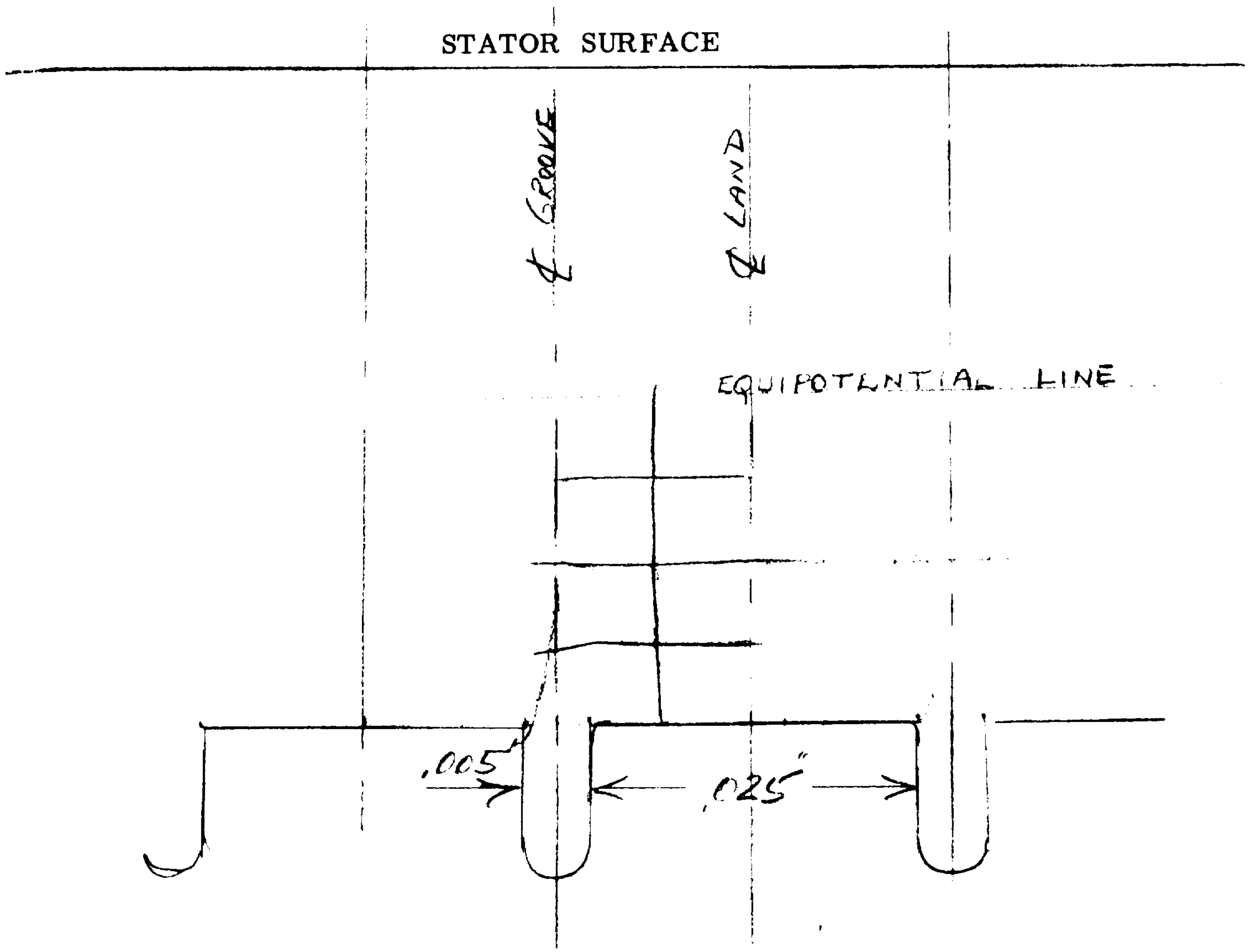
Figure SA1 shows the results obtainable when the rotor grooving is about 10 to 12% of the surface area. This amount of grooving does not change the rotor surface loss a significant amount. To realize a satisfactory reduction in pole face losses, the lands formed by the grooving should be thin; .020" width is a good maximum for 400 cps generators.

To satisfy the requirement for lamination-thickness lands, and only 12% loss of surface, the grooves should be only about .0025" wide and the requirement for such an extremely narrow slot imposes a difficult manufacturing problem. Some methods that can be used to cut the narrow grooves are: diamond sawing with narrow saw or wire, electric-discharge machining with small diameter wire used as electrodes, and electron-beam machining.



DISTRIBUTION OF SURFACE FLUX DENSITIES WHEN A ROTOR POLE-HEAD HAS 50% OF ITS SURFACE CUT AWAY BY GROOVING--ASSUME AN AIR-GAP DENSITY OF 50 KILOLINES PER INCH^2

FIGURE SA-1



WITH .025" LANDS AND .005" WIDE SLOTS, THE POLE SURFACE FLUX DENSITY IS 109% THAT OF A SMOOTH POLE FACE

FIGURE SA-2

FLUX-PLOTTING

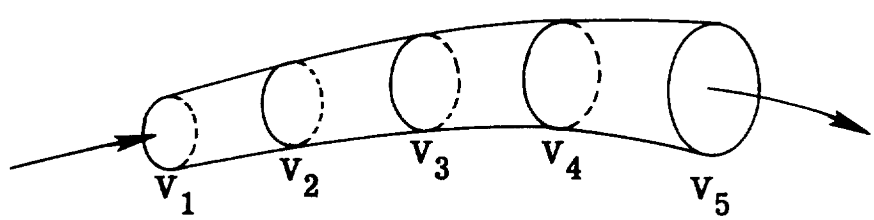
GRAPHICAL FLUX ANALYSIS

Graphical flux analysis is the quickest and most direct solution to many field problems. Irregular or complex fields that yield slowly to mathematical analysis, if at all, can be solved graphically. Manual plots are used to solve heat-flow, air-flow, dielectric field, and flux field problems.

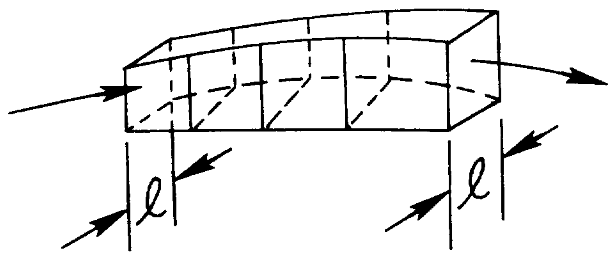
In this study, only flux field distributions are mapped, and only the simplest case is considered -- that is, the case where the iron surfaces are equipotential surfaces and the space between the iron surfaces has the permeability of air. The same total field potential exists across the air space regardless of any change in dimension or configuration.

The permeability of air is constant, so if the field gradient per unit of linear measurement (ampere turns per inch) across the air space changes, the flux density must change by the same ratio.

In making flux plots, the flux is considered to consist of tubes of flux. In a three dimensional field, a single tube is conceived of as looking like this:

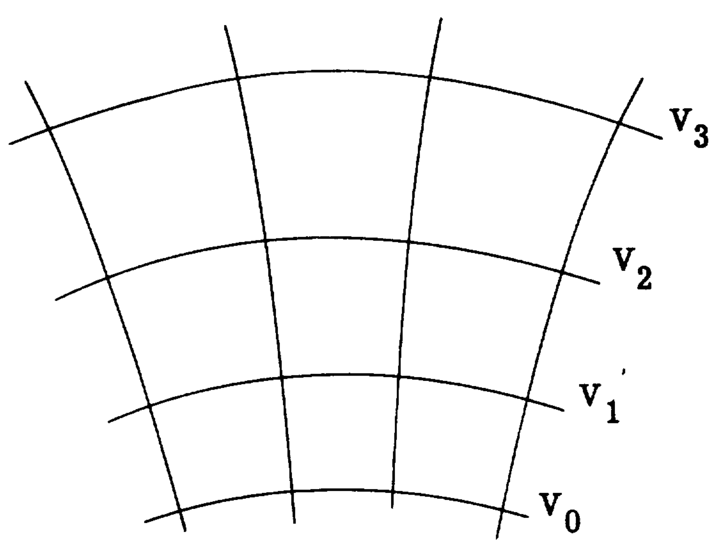


In a two dimensional field, the depth of the tube is constant and the tube looks like this:

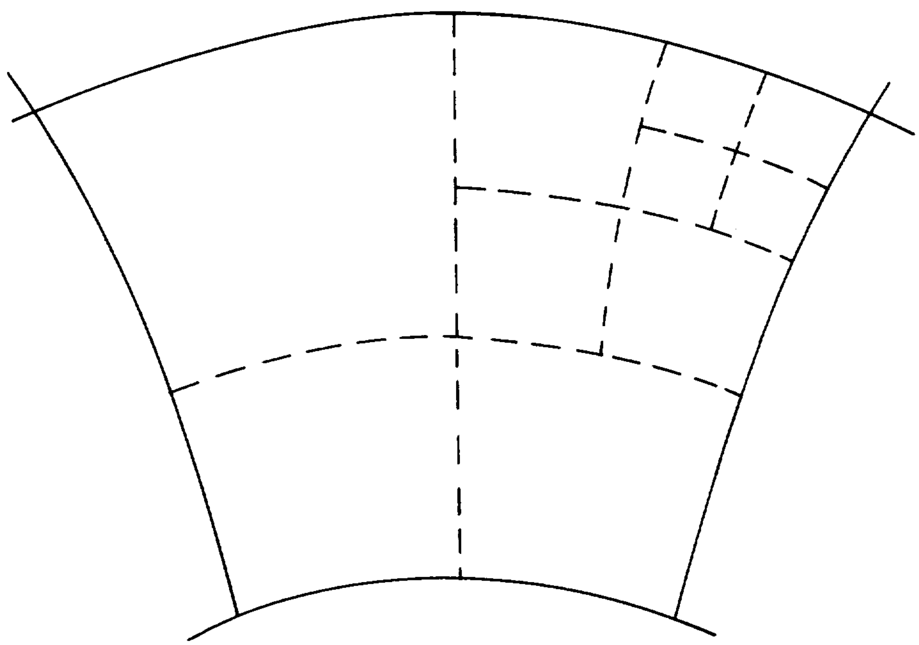


If the number of lines of flux in a tube is held constant, and the depth of the tube is constant, the sides of the tube of flux must converge or diverge in direct ratio to the change in field gradient.

By choosing the scale of field gradient and flux density, the area of flux tube enclosed by the sides of the tube and the equipotential field gradient lines become a square.

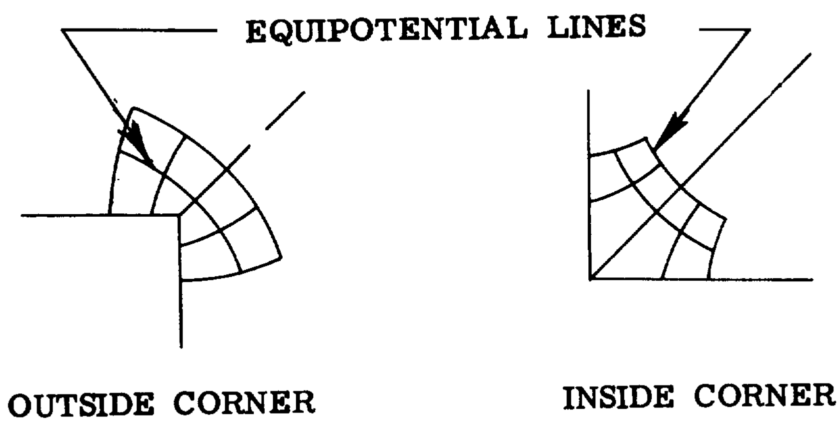


The lines of flux must cross equipotential lines at right angles and enter the iron at right angles. The corners of the areas so defined are right angles and if the squares are successfully divided into fourths, the smaller squares become more closely true squares. In any of the squares, the two dividing lines used to divide the square into four squares will be closely equal in length.



To start a map or flux plot, draw the area to be mapped as large in scale as practical. Ink the boundaries of the iron so erasures will not remove them. Also, ink in the lines of symmetry.

Draw in the middle an equipotential line and then start the plot in the most irregular region or at a corner and a line of symmetry.



Start the maps with large sweeping curves and close the map before trying to perfect the detailed areas.

Use 2H pencil for easy erasures with minimum smudging.

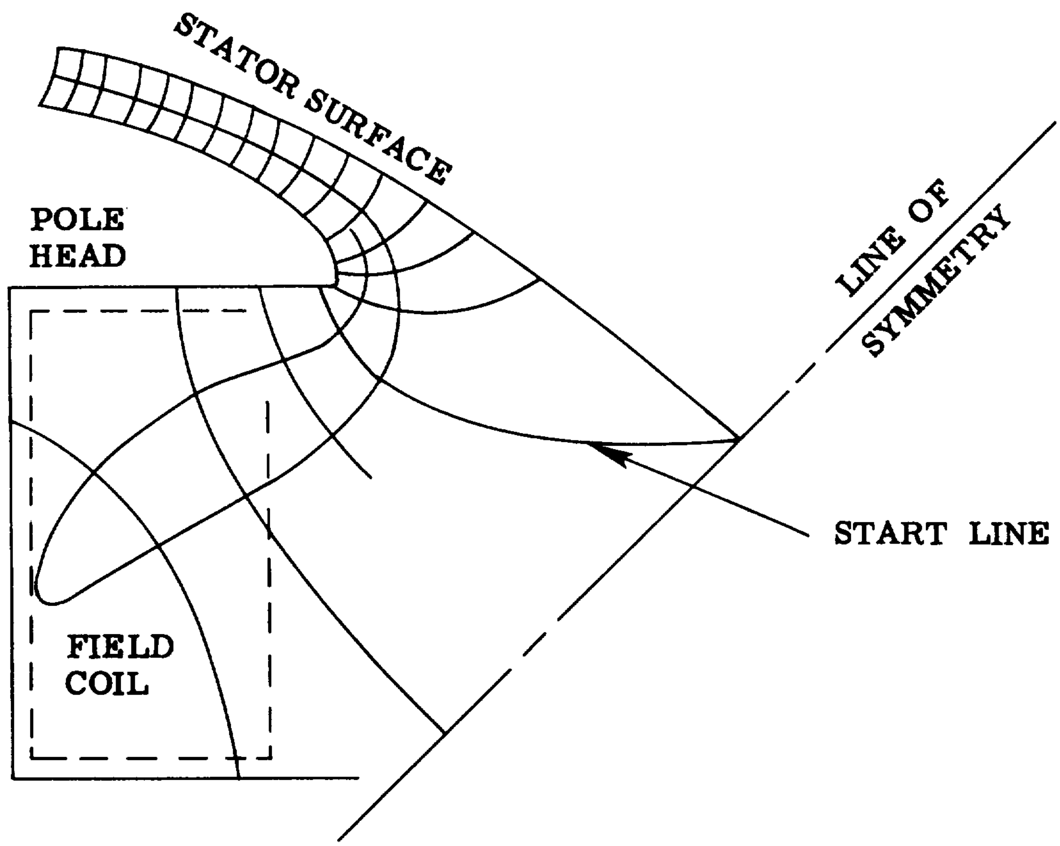
Make large squares and divide only where necessary to check map accuracy or to obtain accurate density.

Intersections between flux lines and equipotential lines must be right angles at all times or the map can not be made accurately.

When the tubes of equal flux are divided, they are most easily divided into multiples of two.

A map can not be forced. However, useable accuracy can be obtained without a precise map, and the operator should exercise his own judgment as to the accuracy required.

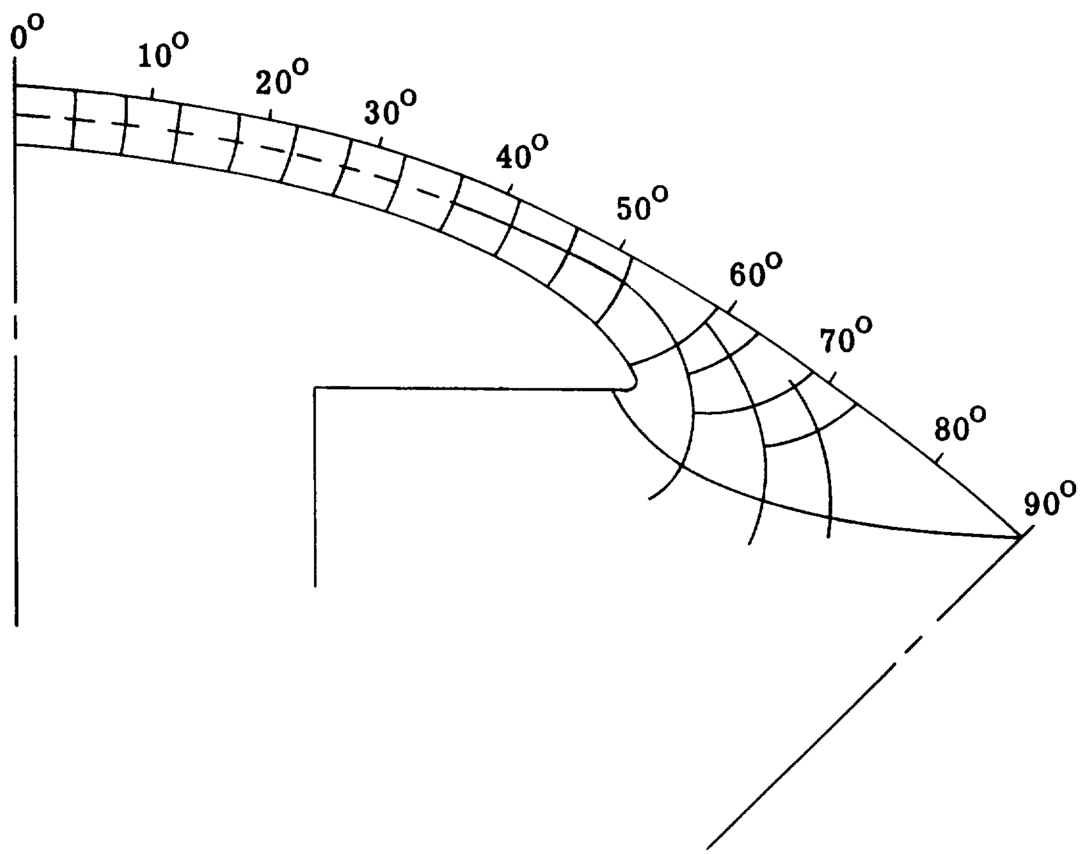
To move lines a small amount, try widening the line with pencil and removing the unwanted portion with a sharp-pointed eraser.



To determine, by means of a freehand flux plot, the no load field form of an electromagnetic machine:

1. Make the flux plot in the manner described in the literature, with all intersections of flux lines and equipotential lines at right angles and with all curvilinear squares capable of being divided into smaller, curvilinear squares.

2. The distance from centerline between poles to the centerline of the pole is 90 electrical degrees. Divide this arc on the stator surface into 10^{0} increments.

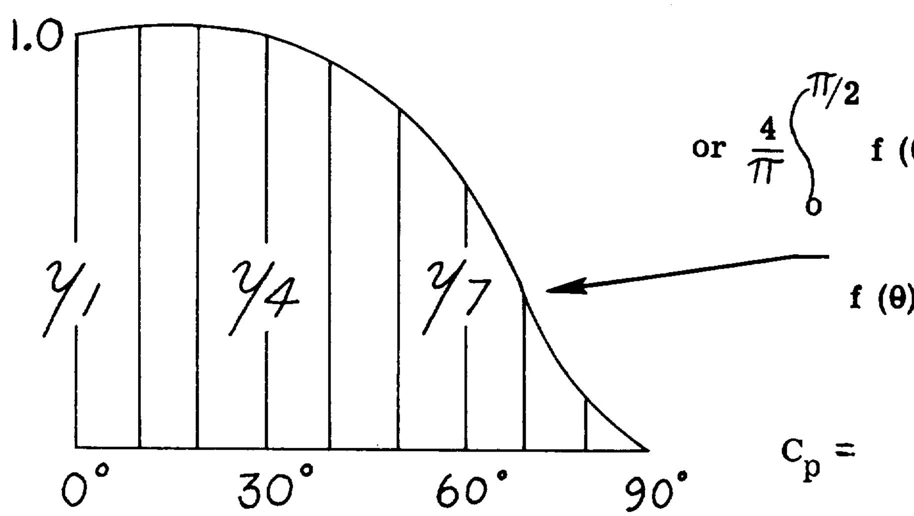


3. At any point on the stator surface, the distance from the surface to the first equipotential line is proportional to the flux density at that point. A plot of flux density, therefore, is a plot of the ratio of distance from the stator surface to the first equipotential line. Where the equipotential lines have been further divided, the distance ratios increase proportionately.

4. The maximum density (usually at the pole head centerline) can be used as a one per unit; 1.0 or 100%.

$$C_1 = \text{Ratio } \frac{\text{Fundamental}}{\text{Actual}} = \frac{2}{\pi}\int_0^{\pi} f(\theta)\sin\theta\, d\theta$$

$$\text{or } \frac{4}{\pi}\int_0^{\pi/2} f(\theta)\cos\theta\, d\theta$$



$$C_p = \frac{1}{N}\int_0^N Y_N$$

Cos 0^o = 1.000	Y1 (.5) =	(.5)	Y_1 =
Cos 10^o = .985	Y2 (.985) =		Y_2 =
Cos 20^o = .940	Y3 (.940) =		Y_3 =
Cos 30^o = .866	Y4 (.866) =		Y_4 =
Cos 40^o = .766	Y5 (.766) =		Y_5 =
Cos 50^o = .643	Y6 (.643) =		Y_6 =
Cos 60^o = .500	Y7 (.500) =		Y_7 =
Cos 70^o = .342	Y8 (.342) =		Y_8 =
Cos 80^o = .173	Y9 (.173) =		Y_9 =
Cos 90^o = .000			

$9\,\overline{\big)\,\sum_{Y_1}^{Y_9}}$ $\qquad$ $9\,\overline{\big)\,\sum_{Y_1}^{Y_9}}$

C_1 = $\qquad$ C_p =

Ref: Mathematics of Modern Engineering, Vol 1, pp 73-92, Doherty and Keller.

References to use for a study of Flux-Mapping techniques are:

"Graphical Flux Analysis in Transformer Design", M.G. Leonard, Electro-Technology, Oct., 1961, pp 122-128.

"Fundamentals of Electrical Design", A.D. Moore, McGraw-Hill Book.

"Electromagnetic Devices", H.C. Roters, John-Wiley & Sons Book.

Notes on Air-Gap and Interpolar Induction, F.W. Carter, IEE Proc. (British), Vol 29, 1900, p 925.

Air Gap Induction, F.W. Carter, El. World, Vol. 38, p 884.

Sketches of Magnetic Fields in Iron, Th. Lehmann, Rev. Gen. El., Vol. 17, 1926

Mapping Magnetic and Electrostatic Fields, A.C. Moore, El. J., Vol. 23, 1926, p 355.

Fundamental Theory of Flux Plotting, A.R. Stevenson, G. E. Rev., Vol. 29, 1926, p 797.

Graphical Determination of Magnetic Fields, R.W. Wieseman, AIEE Trans., Vol. 46, 1927, p 430.

Graphical Determination of Magnetic Fields, E.E. Johnson and C.H. Green, AIEE Trans., Vol. 46, 1927, p 136.

Graphical Determination of Magnetic Fields, A.R. Stevenson and R.H. Park, AIEE Trans., Vol. 46, 1927, p 112.

The Interpolar Fields of Saturated Circuits, T. Lehmann, AIEE Trans., Vol. 46, 1927, p 1411.

A Practical Application of Graphical Flux Mapping, J.F. Calvert, El. J., Vol. 24, 1927, p 543.

Graphical Flux Mapping, J.F. Calvert and A.M. Harrison, El. J., Vol. 25, 1928. Theory and General Discussion, p 147; Fields of Non-Salient Pole Synchronous Machines, p 179; D-C Motors and Generators, p 399; D-C Motor, Salient Pole Synchronous Machine, Universal Motor, etc., p 510.

Analytical Determination of Magnetic Fields, B.L. Robertson and I.A. Terry, AIEE Trans., Vol. 48, 1929, p 1242.

Magnetic Fields in Machinery Windings, J.F.H. Douglas, AIEE Trans., Vol. 54, 1935, p 959.

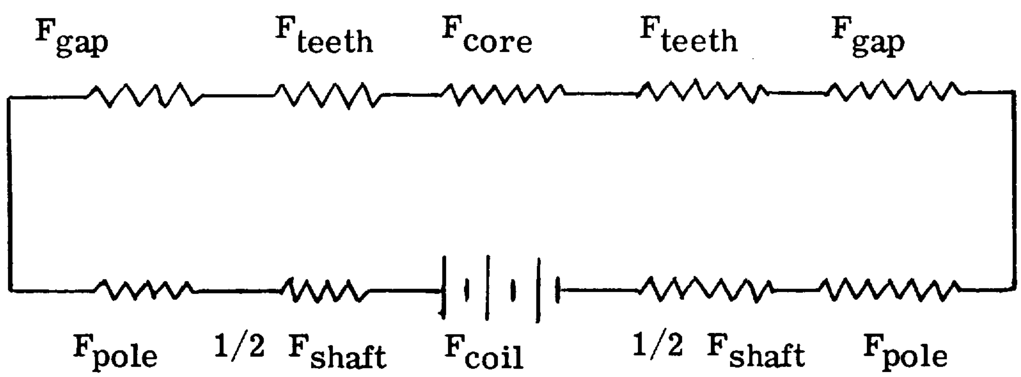
THE MAXIMUM $\frac{\ell}{d}$ RATIO FOR ROTATING COIL LUNDELL GENERATORS

In Brief

The maximum practical $\frac{\ell}{d}$ ratio for a rotating coil Lundell generator is .3.

Discussion

The flux circuit of a rotating-coil Lundell generator can be represented by the mmf drops below:



The rotor shaft completes the flux circuit, and the area of the shaft limits the useful stator length by limiting the amount of flux that can be carried inside the excitation coil.

When a maximum length machine is made, about .50% of the stator bore cross-section area is used up or made unavailable because of the thickness of the cantilevered poles at their bases.

Another 20% of the stator bore cross-section area must be used for an excitation coil and only about 30% of the area can be utilized for shaft.

Assumptions are:

Area Shaft $= .3 \frac{\pi d^2}{4}$

Gap Density $= 35$ Kl/in^2

Shaft Density at FL $= 100$ Kl/in^2

Pole Embrace $= .6$

Total Flux at FL $= 2.5$ x useful flux. (This assumes that the leakage flux is 1-1/2 times the useful flux).

Then:

Total Pole Flux $= \pi d \ell (35)\ C_p$ Kilolines for all poles (this flux links the stator winding).

Half of this flux passes through the shaft.

Total Shaft Flux at FL =

$$\phi_{sh} = 2.5 \frac{\phi_T C_p}{2} = \frac{2.5(.6)}{2} \pi d \ell (35)$$

$$= 26.2 \pi d \ell$$

ϕ_{sh} also $= 100 \frac{\pi d^2}{4} (.3) = 7.5 \pi d^2 = B_{sh}$ (Area of Shaft)

$$26.2 \pi d \ell = 7.5 \pi d^2$$

$$\ell = \frac{7.5}{26.2} d = .286d$$

This can be rounded off to .3.

THE MAXIMUM $\frac{\ell}{d}$ RATIO FOR TWO, INSIDE, STATIONARY COIL LUNDELL GENERATORS (OR BECKY-ROBINSON GENERATORS)

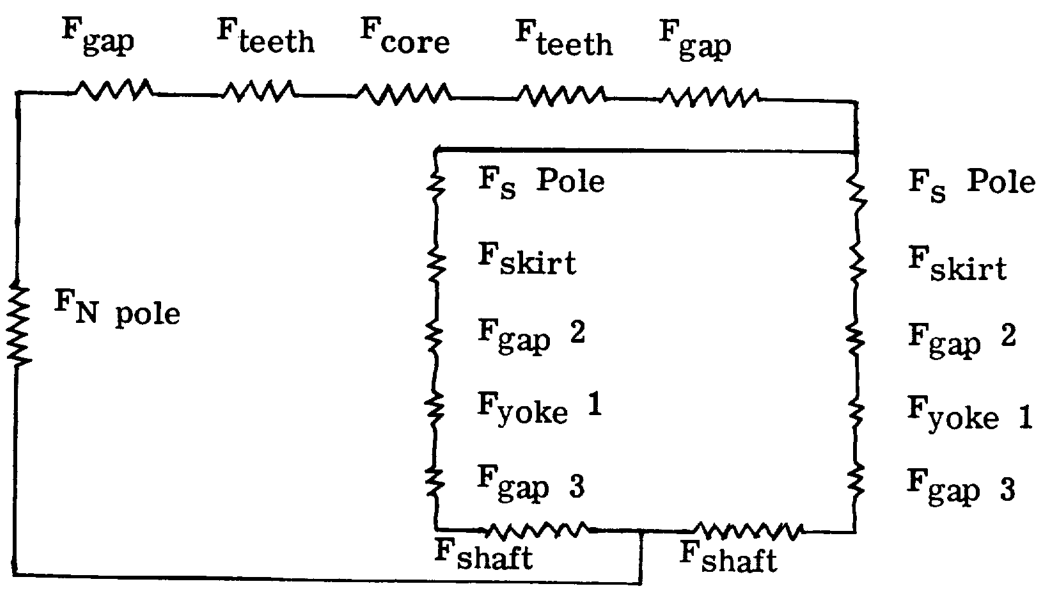
In Brief

The maximum practical $\frac{\ell}{d}$ ratio for a Becky-Robinson type of stationary-coil Lundell Generator is approximately:

$$\frac{\ell}{d} = .53$$

Discussion

The flux circuit of a two-coil Lundell generator of the Becky-Robinson type is represented by the mmf drops shown below.



Note that the flux in one parallel branch circuit must pass through the rotor skirt, or flux collector ring, into the yoke and back through the shaft.

The combined shaft and flux collector ring areas must carry the equivalent of the total flux that passes into and back out of the stator. The areas of the combined skirt or collector ring and shaft cannot greatly exceed 60% of the total cross-section area of the stator bore because of the room needed for the excitation coil.

The following assumptions are now made:

Shaft and skirt area $= .6 \dfrac{\pi d^2}{4}$

Shaft and skirt density $= 100\ K\ell/in^2$

Air-Gap density $= 35\ K\ell/in^2$

Total flux in shaft $=$ 2.5 times useful flux

The combined areas of the rotor skirt plus shaft should be equal to the combined shaft areas at the two ends or skirt area $=$ shaft area.

$$2.5 \text{ x shaft flux} = .6 \frac{\pi d^2}{4} (100)$$

$$= 15 \pi d^2$$

$$\text{Useful flux} = \frac{(15)}{2.5} \pi d^2 = 6 \pi d^2$$

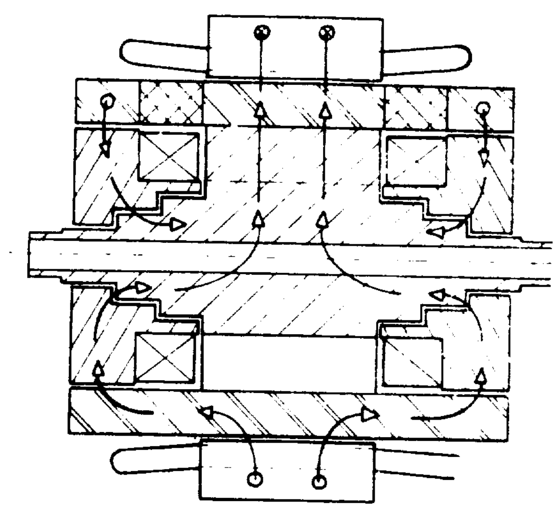
$$\text{Also, Useful flux} = \frac{\pi d \ell (35)}{2} C_p\ K\ell \text{ in shaft}$$

$$6 \pi d^2 = \frac{35 \pi d \ell}{2} \quad (C_p = .65)$$

$$6d = \frac{35 \ell (.65)}{2} = 11.4 \ \ell$$

or $$\ell = \frac{6d}{11.4} = .53 \ d$$

TWO-COIL, INSIDE-COIL LUNDELL
OR BEKEY-ROBINSON GENERATOR



THE DEVELOPMENT OF EQUATIONS DESCRIBING THE WEIGHTS OF ELECTROMAGNETIC PARTS FOR THREE GENERATOR TYPES

A weight breakdown is made for the electromagnetic parts of 1) two, inside, stationary-coil Lundell generators (Becky-Robinson Generators), 2) two, outside-coil Lundell generators (Rice Generators) and 3) Homopolar Inductors.

In order to have simple but realistic relationships between the three generator types mentioned above, some simplifying assumptions have been made.

1. In all cases, the tooth width is equal to the slot width.
2. A pole embrace of .65 is used and the pole constant is therefore approximately .65.
3. The gap density B_g is 50 $K\ell/in^2$ for one set of calculations, and 35 $K\ell/in^2$ for another set of calculations.
4. To keep the machine reactances of the 4 pole, 6 pole, 8 pole generators approximately constant for comparison purposes, we have assumed that the gap density is constant and that ampere wires divided by poles times air gap length is also constant.

$$\frac{A}{P\ g_e} = \text{constant.}$$

For 4-pole a-c generators A = 600

For 6-pole a-c generators A = 700

For 8-pole a-c generators A = 800

As a matter of academic interest, the gaps are:

8-pole generator gap = g

6-pole generator gap = 1.16 g

4-pole generator gap = 1.5 g

In the programs note that all the reactance formulae are multiplied by a common factor designated as X.

$$X = \frac{A\ K_d}{2\ C_1\ B_g\ (10)} = AK. \quad \text{When Bg is constant, then}$$

$$X_{ad} = X\ C_1\ C_m \lambda_a = AK' \ \frac{d}{P\ ge} = \text{constant and } \frac{A}{P\ ge} = \text{constant.}$$

The constant-reactance approximation as stated is inaccurate by the variation in d when the number of poles is changed. This variation in diameter ($\pm$ 10%) can be compensated for by further changing the length of the air-gap to keep the reactance constant. The assumption is realistic enough to allow useful weight comparisons between the three types of generators.

SLOT DEPTH (h_s)

If a stator loading of 800 ampere wires/inch of stator is assumed and the slot width is equal to the tooth width there are 800 amperes in 1/2 inch of stator bore periphery. For 8,000 ampere/in^2 current density in the stator winding and a slot fill factor of 2/3, $\frac{800}{8000(.67)}$ = .150 in^2 of slot is needed. The slot must be about $\frac{.150}{.5}$ = .3" deep. For a machine with a stator bore diameter of 6", a .3" deep slot is .05 d and this slot depth estimate has been used in all calculations.

CORE DEPTH (h_c)

The useful flux per pole in the stator is $\phi_P = \frac{\pi d \ell B_g C_p}{P}$ Kℓ, and the area of the bore cross-section is $h_c \ell$. If the core density is 80 Kℓ/in^2 then,

$$\frac{\phi_P}{2 A_c} = 80 \text{ and}$$

$$h_c = \frac{\pi d \ell B_g C_p}{2P\, 80 \ell} = \frac{\pi (B_g)\, .65\, d}{2\,(80)\, P}$$

$$= \frac{.01275\, (B_g)\, d}{P}$$

For 50 Kℓ/in^2 gap density $h_c = .638 \frac{d}{P}$

For 35 Kℓ/in^2 gap density $h_c = .446 \frac{d}{P}$

OUTSIDE DIAMETER OF STATOR (D)

The outside diameters of the stators are $d + 2h_s + 2h_c$

$$h_s = .05\ d \text{ in all cases}$$

$$h_c = .638\ \frac{d}{P} \text{ for } 50\ K\ell/in^2$$

$$= .446\ \frac{d}{P} \text{ for } 35\ K\ell/in^2$$

$$D = (1.1)\ d + \frac{1.276d}{P} \text{ for } 50\ K\ell/in^2 \text{ gap density}$$

$$= (1.1 + .319)\ d = 1.419\ d \text{ for } 4P$$

$$= (1.1 + .212)\ d = 1.312\ d \text{ for } 6P$$

$$= (1.1 + .16)\ d = 1.26\ d \text{ for } 8P$$

$$D = 1.1\ d + .892\ \frac{d}{P} \text{ for } 35\ K\ell/in^2 \text{ gap density}$$

$$= (1.1 + .223)\ d = 1.32\ d \text{ for } 4P$$

$$= (1.1 + .147)\ d = 1.25\ d \text{ for } 6P$$

$$= (1.1 + .111)\ d = 1.21\ d \text{ for } 8P$$

YOKE THICKNESS HOMOPOLAR INDUCTOR

The leakage flux of the homopolar inductor is assumed to be all of the flux that is not useful in generating voltage and is assumed to be .4 the useful flux. This is a low estimate that can only be realized with careful design and is an estimate that makes the homopolar inductor compare favorably with the other machines.

any diameter of the end-bell the weight of the end bell must be

$$\text{EB wt.} = \pi(D + t_y)\, t_y \left[\frac{D-d}{2}\right] .283 + \text{flux shoe weight estimated at}$$

$$.125\ (\text{END-BELL WEIGHT}) = \text{EB wt.} = \pi(1.125).283 \left[D + t_y\right] t_y \left[\frac{D-d}{2}\right] \text{ lbs.}$$

ROTORS OF OUTSIDE-COIL LUNDELLS

The length of the rotors for outside-coil Lundells must be about 3ℓ to accommodate the flux-collector rings at the rotor ends. When the environment and speed permits the rotor can be made approximately 50% solid.

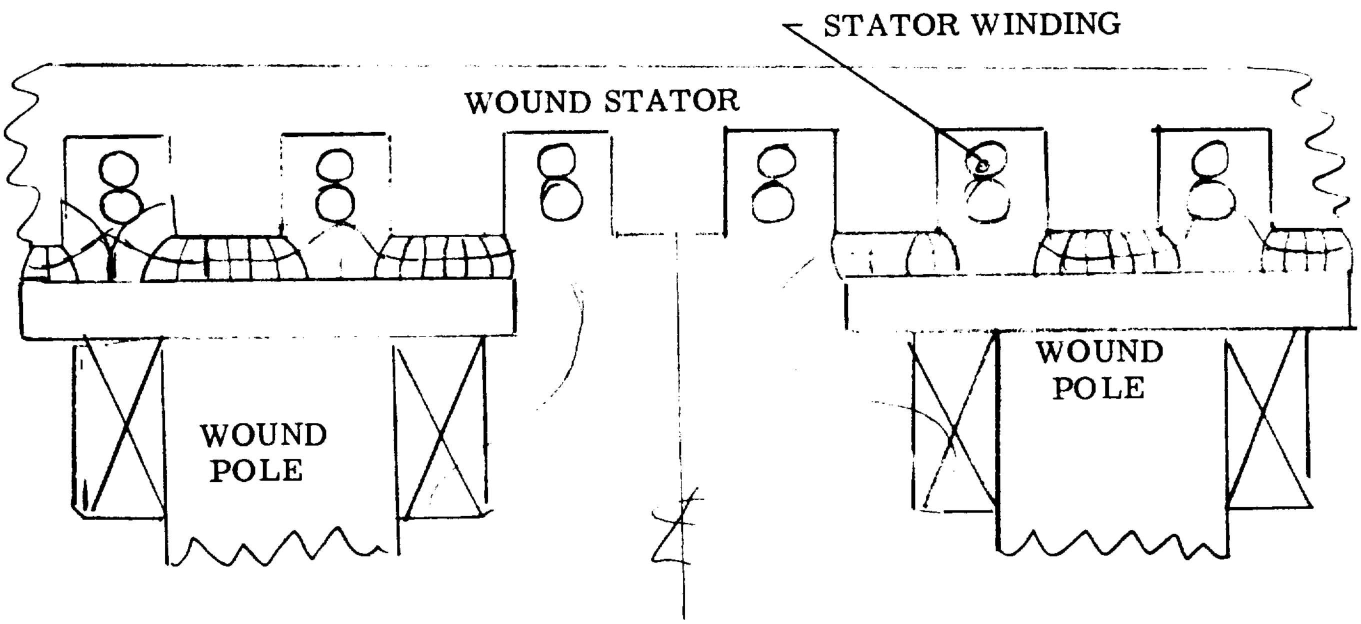
$$\text{Wt. of rotor} = \frac{\pi d^2}{4} \quad \frac{3}{2}\, d \ (.5)\ (.283)$$

$$= .166\, d^3 \quad \text{lbs.}$$

ROTOR AND FIELD-COILS FOR TWO, INSIDE-COIL LUNDELLS (BECKY ROBINSON)

To accommodate the field coils and yokes in the rotor ends, the rotor of the two, inside, stationary-coil Lundell must be approximately 2ℓ long. Since $\ell = \frac{d}{2}$, the rotor length is $\frac{2d}{2} = d$. The rotor is considered 80% solid to account for the coils and yokes.

$$\text{Rotor wt.} = \frac{\pi d^2}{4}\, d\ (.283) = .333\, d^3 \quad \text{lbs.}$$



If:

1) The slots occupy 50% of the space in the stator bore area.

2) The no load flux density in the iron is 100 $K\ell/in^2$.

Then the air gap density will be 50 $K\ell/in^2$ at no load.

In practice, the air gap density may vary from 20 $K\ell/in^2$ for a permanent-magnet generator to 65 $K\ell/in^2$ for a low-reactance wound-pole generator. Solid-pole generators usually operate at moderate gap densities because of pole-face losses ,

The ampere-wires per inch of bore periphery A represents the current loading of the generator and the output power. If the value A is doubled and all else held constant, the power output doubles. In a 30 KVA, 8-pole MIL-G-6099A generator for air-craft, the value A will be about 700 to 800. The tooth width will about equal the slot width, the gap density is approximately 50 $K\ell/in^2$ and the tooth no load density is about 100 $K\ell/in^2$.

$$\text{Yoke area} = \pi (D + t_y)\, t_y$$

$$= \pi (D)\, t_y \text{ approximately}$$

$$\text{Yoke flux} = \frac{\pi\, d\, \ell\, B_g C_p}{2} \quad \text{Kilolines of useful flux}$$

$$\text{Yoke flux} = 80 \text{ x yoke area}$$

$$\ell = \frac{d}{2}$$

$$\text{Yoke area} = \frac{\pi d^2\, B_g\, C_p}{4(70)}$$

$$\pi\, D\, t_y = \frac{\pi\, d^2\, B_g\, C_p}{280}$$

$$t_y = \frac{d^2\, B_g\, (.65)}{D(280)}$$

$$= \frac{d \;\; (50)\,.65}{1.42\,(280)} = .0817\, d$$

For 4 poles and $B_g = 50$

$\rho = .283$ lb/in³

$$\text{Yoke weight} = \pi (D + t_y)\, t_y\, \frac{d}{2} \times 3\, (.283)$$

$$= \pi (1.42 + .082)\, .082\, \frac{d^3}{2} \times 3\, (.283)$$

$$= .164\, d^3 \text{ lbs. for } B_g = 50 \text{ and } P = 4.$$

ROTOR, HOMOPOLAR INDUCTOR

The rotor of the homopolar inductor is assumed to be 60% solid on the ends and 100% solid in the center section between the stators. The diameter of the center section or shaft area is .8 d. The rotor length is ℓ per section or $\frac{d}{2}$ per section.

$$\text{Rotor weight} = \left[\frac{\pi d^2}{4}\ \frac{d}{2}\ (.60) \times 2 + \right.$$

$$\left. + \frac{\pi (d \times .8)^2}{4}\ \frac{d}{2}\right] .283 \text{ lbs.}$$

$$= \frac{.283}{8}\ d^3 \left[1.2 + .64\right] = .204\ d^3 \text{ lbs.}$$

YOKE AND END-BELLS OF OUTSIDE-COIL LUNDELL GENERATORS

The useful flux in the yoke is $\frac{\pi d \ell B_g C_p}{2}$ Kilolines and the leakage flux is $\frac{2}{3}$ as great as the useful flux. The flux density in the yoke, due to the useful flux alone is 60 $K\ell/in^2$.

Area yoke $= \pi D\, t_y$ approx.

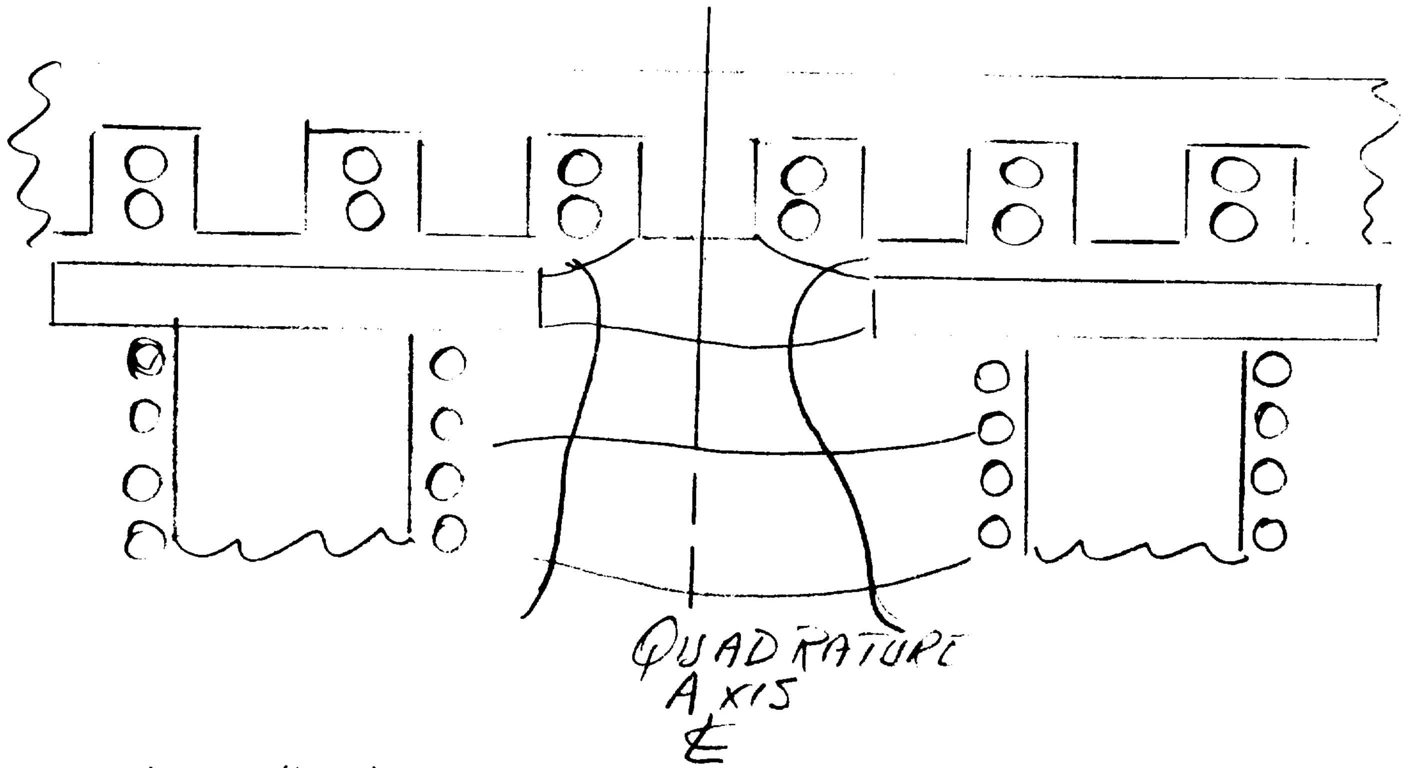
$$t_y = \text{thickness of yoke} = \frac{\pi \frac{d^2}{4}\ .65(B_g)}{\pi D\ (60)}$$

$$\text{Yoke length} = 3\ell = 3\frac{d}{2}$$

$$\text{Yoke weight} = \pi (D + t_y)\, t_y\ \frac{3}{2}\ d\ (.283) \text{ lbs.}$$

The end bells of the two, outside coil Lundell generators must carry the yoke flux and must have approximately constant cross-section area from the outer yoke to the auxiliary air gap. If $\pi\, d_{EB}$ (thickness) = constant at

The limit of ampere loading on the stator is reached when additional rotor ampere turns, which would be necessary to overcome more armature reaction and armature voltage drop, only serve to force more flux across the rotor leakage paths.



A small (1 KW) conventional, 8000 rpm, 400 cycle permanent magnet generator with block-type salient-pole magnets will produce about 600 ampere wires/inch at maximum output. The regulation is about 40% at such a load and in order to maintain a useable voltage level about 250 ampere wires/inch is the usual limit.

A 10 KVA, 4-pole, wound rotor, salient-pole MIL-G-6099A generator may have a rated load output of about 500 to 600 ampere-wires per inch.

A 30 KVA, 2-pole, 400 cps, non-salient pole generator may only be able to carry 400 ampere-wires/inch if it is to meet MIL-G-6099A performance requirements.

There is no direct and clear-cut way to arrive at the maximum stator loading. For different applications, the load limit may be entirely different. In general though, for any of the electromagnetic generators we are likely to be interested in the loading A will probably lie between 600 and 900. For very small machines and PM generators, this value may be as low as 200 while for large synchronous condensers on utility systems (50,000 KVA) the value may be 1200.

The ampere loading of the stator is related to the reactances of the machine.

If wire is wound through an iron or steel machine, it acquires inductance.

$$L = \frac{N\phi}{i} = \frac{N\,(Ni)\,\mathcal{P}}{i}$$

$$= N^2\mathcal{P} \qquad \text{Where } \mathcal{P} = \text{ permeance}$$

This indicates that since the output current is fixed in any specific application, the inductance of the stator winding will vary directly as the square of the conductors/inch used or as A^2.

GROUPING OF FRACTIONAL SLOT WINDINGS

When the stator is comprised of a winding having fractional slots per pole, the grouping of the coils can be determined by the following method.

Express the ratio of the number of slots to the number of poles as an improper fraction reduced to its lowest terms. The denominator will then represent the number of poles in a repeatable section and the numerator will then be the number of slots in a repeatable section. If the number of slots in a repeatable section is not divisible by the number of phases a balanced polyphase winding cannot be obtained.

The maximum number of parallel paths in the winding is found by dividing the number of poles of the machine by the number of poles in a repeatable section. This gives the maximum possible number of parallels.

To determine the grouping lay out a table having as many horizontal divisions as there are slots per repeatable section, and as many vertical divisions as there are poles per repeatable section. Divide the horizontal divisions into m number of phases and using a pitch of y = poles per repeatable section lay out the winding.

As an example consider a 3 phase, 20 pole, 84 slot machine, then 84/20 = 21/5 = (slots per repeatable section)/(poles per repeatable section). The maximum number of parallels possible = 20/5 = 4, and the available number of parallels will then be 4 and 2. Lay out the table as follows with y = 5 and throw = 1-6.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	x					x					x					x					x
2					x					x					x					x	
3				x					x					x					x		
4			x					x					x					x			
5		x					x					x					x				

Phase a (slots 1–7) | Phase c (slots 8–14) | Phase b (slots 15–21)

The grouping will thus be 21211-21211 = 21211 = and repeat 3 x 4 = 12 times. The coils will then be placed as follows:

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Phase of Coil	+a	+a	-c	+b	+b	-a	+c	-b	-b	+a	-c	-c	+b	-a	+c	+c	-b	+a	+a	-c	+b
Grouping	2		1	2		1	1	2		1	2		1	1	2		1	2		1	1

Another way of accomplishing the same result as that given above is as follows:

Since there are 5 poles per repeatable section and 21 slots per repeatable section there must be 7 slots per phase in each repeatable section with these 7 slots occupying positions over 5 poles. The coils in a section may be arranged in any order but the best arrangement in general is that which gives the largest distribution factor. Usually the most symmetrical arrangement of the coils is best, or in this case 12121. Laying out the winding of the previous example for the 12121 arrangement gives:

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Phase of Coil	+a	-c	-c	+b	-a	-a	+c	-b	+a	+a	-c	+b	+b	-a	+c	-b	-b	+a	-c	-c	+b
Grouping	1	2		1	2		1	1	2		1	2		1	1	2		1	2		1

which is the same as that arrived at previously with the exception that it is displaced several slots.

THE SLOT STAR

The two above methods of grouping can be verified by the slot star method.

In general let the number of slots per phase per pole q be represented as $q = N/B = a + b/B$. where a is an integer. Then the winding repeats itself after each B poles and the number of recurrent groups is equal to P/B. Each

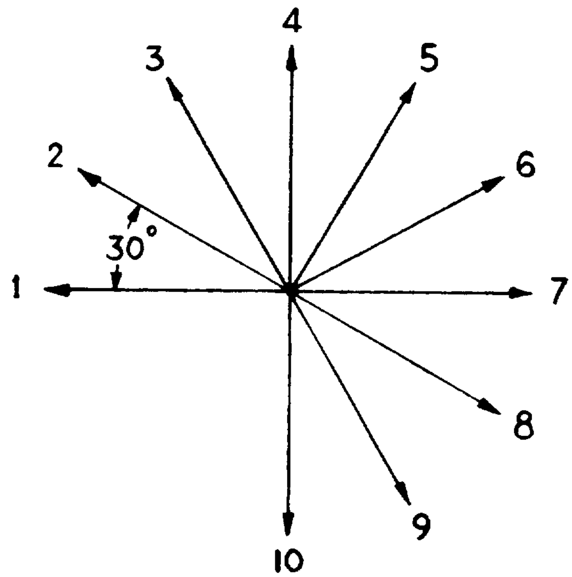


FIGURE SA-1

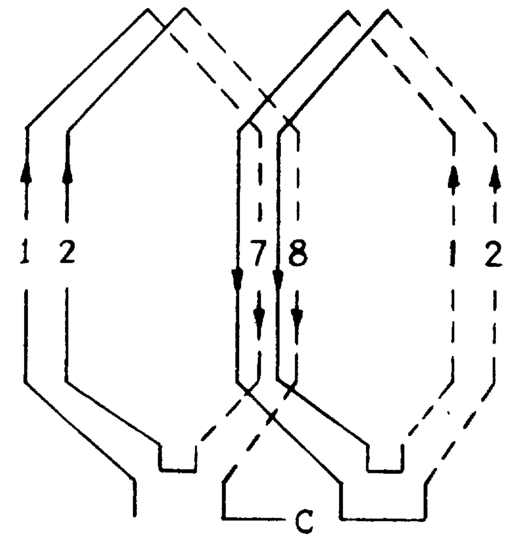


FIGURE SA-2

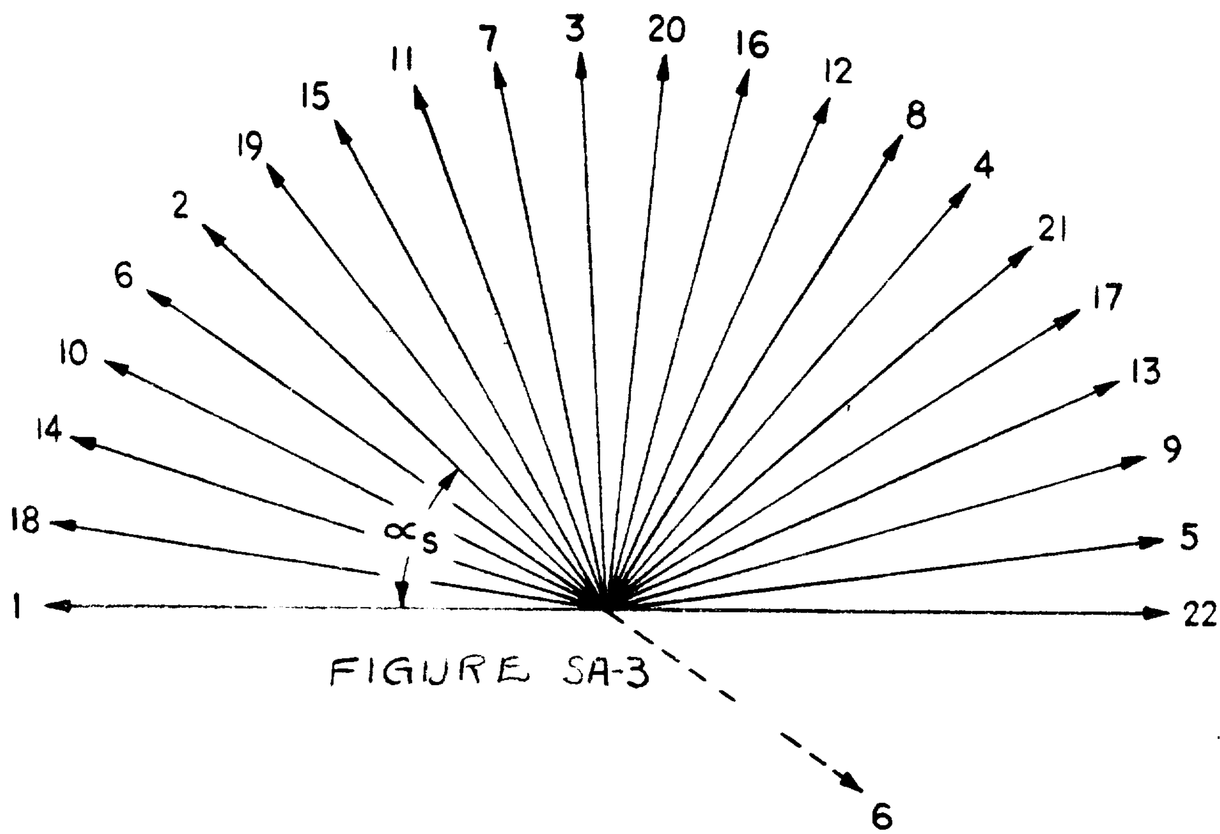


FIGURE SA-3

phase has N slots in B poles. Further, each phase has B - b coil groups with a coils and b coil groups with a + 1 coils in B poles. If B/m equals an integer there cannot be a perfectly balanced fractional slot winding.

Apply the above rules to the 3 phase, 20 pole, 84 slot example gives $q = 84/(20 \times 3) = 7/5 = 1 + 2/5$. Thus the winding repeats itself after each 5 poles the number of recurrent groups is $20/5 = 4$. Each phase has 7 slots in 5 poles and each phase had $5 - 2 = 3$ coil groups with 1 coil and 2 coil groups with $1 + 1 = 2$ coils in 5 poles.

The slot star of a 2 pole, 3 phase integral slot winding with q equals two is shown in Figure 1. The angle between two adjacent slots is $\alpha_s = 180^\circ/mq = 30^\circ$.

Two adjacent vectors correspond to two adjacent slots and thus slots 1, 2, 7, and 8 belong to phase I, slots 3, 4, 9, and 10 belong to phase II and so on. Vector 7 with which the second pole starts is shifted 180° with respect to vector 1, and the same applies for vectors 2 and 8, 3 and 9, etc. Therefore the bottom half of the slot star is the same as the top half except that their vectors are shifted by 180°.

The four coils of phase 1 are shown in Figure 2 with the solid lines representing the tops of the slots and the dotted lines representing the bottom. The connector C takes care that all the emfs add together and thus the slot star of this example is completely represented by only half of the circle.

The above type of star will then apply to the integral slot windings in general.

In the fractional slot winding, B poles make the recurrent group and just as for the integral slot winding the slot star of B poles is represented by half of a circle.

Figure 3 shows the slot star of the 20 pole, 3 phase, 84 slot example. There are 5 poles in B with $7 \times 3 = 21$ slots per recurrent group. $\alpha_s = 180/(3 \times 1.4)$

= 42 and 6/7^{o}. Thus the angles which correspond to the slots are:

Slot No.	1	2	3	4	5	6
α_s	- 0	42 6/7	85 5/7	128 4/7	171 3/7	214 2/7 = 34 2/7 etc.

Since the largest distribution factor for the fundamental is obtained when the slots belonging to each group are closest together, the first seven slots in the slot star will be assigned to phase a. The second seven to phase c, and the last seven to phase b. Thus slots 1, 18, 14, 10, 6, 2, and 19 are phase a; 15, 11, 7, 3, 20, 16, and 12 are phase c; and 8, 4, 21, 17, 13, 9, and 5 are phase b.

The grouping then becomes

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Phase of Coil	+ a	+ a	- c	+ b	+ b	- a	+ c	- b	- b	+ a	- c	- c	+ b	- a	+ c	+ c	- b	+ a	+ a	- c	+ b
Grouping	2		1	2		1	1	2		1	2		1	1	2		1	2		1	1

This is identical with the grouping of the first method and therefore verifies its accuracy.

In the integral slot winding the beginnings of the phases are displaced by 120 and 240 electrical degrees. Also in the fractional slot windings the distances between the beginnings of the phases can be made 120 and 240^{o}. This will be the case when the beginnings are placed in slots 1, 1 + N, and 1 + 2N when B is an even number, and in slots 1, 1 + 2N, and 1 + (1 + m) N, when B is an odd number. This arrangement of the beginnings of the phases will place them far apart from each other mechanically while it is often desirable to have them near to each other. In order to place the beginnings of the phases near to each other the beginnings can be placed approximately 120 and 240 electrical degrees apart and the windings still will be balanced. This is due to the fact that in the fractional slot winding the emfs of the consecutive coil groups are not in phase and the sequence of the geometric addition of the single emfs is of no influence on the resultant phase emf. So in the example considered the beginnings of the phases can be placed in slot 1 for phase a, slot 4 for phase b, and slot 7 for phase c. The angles between the beginnings are then 128 and $4/7^{o}$, and 257 and $1/7^{o}$.

DISTRIBUTION FACTOR

The voltages induced in the separate coils of a distributed winding are not in exact phase and their resultant is therefore less than would be produced in a concentrated winding having the same number of turns. The ratio of the voltages produced by distributed and concentrated windings having the same number of turns is called the distribution factor. In the case of integral slots per phase per pole it can be derived as follows:

θ = electrical angle per phase group

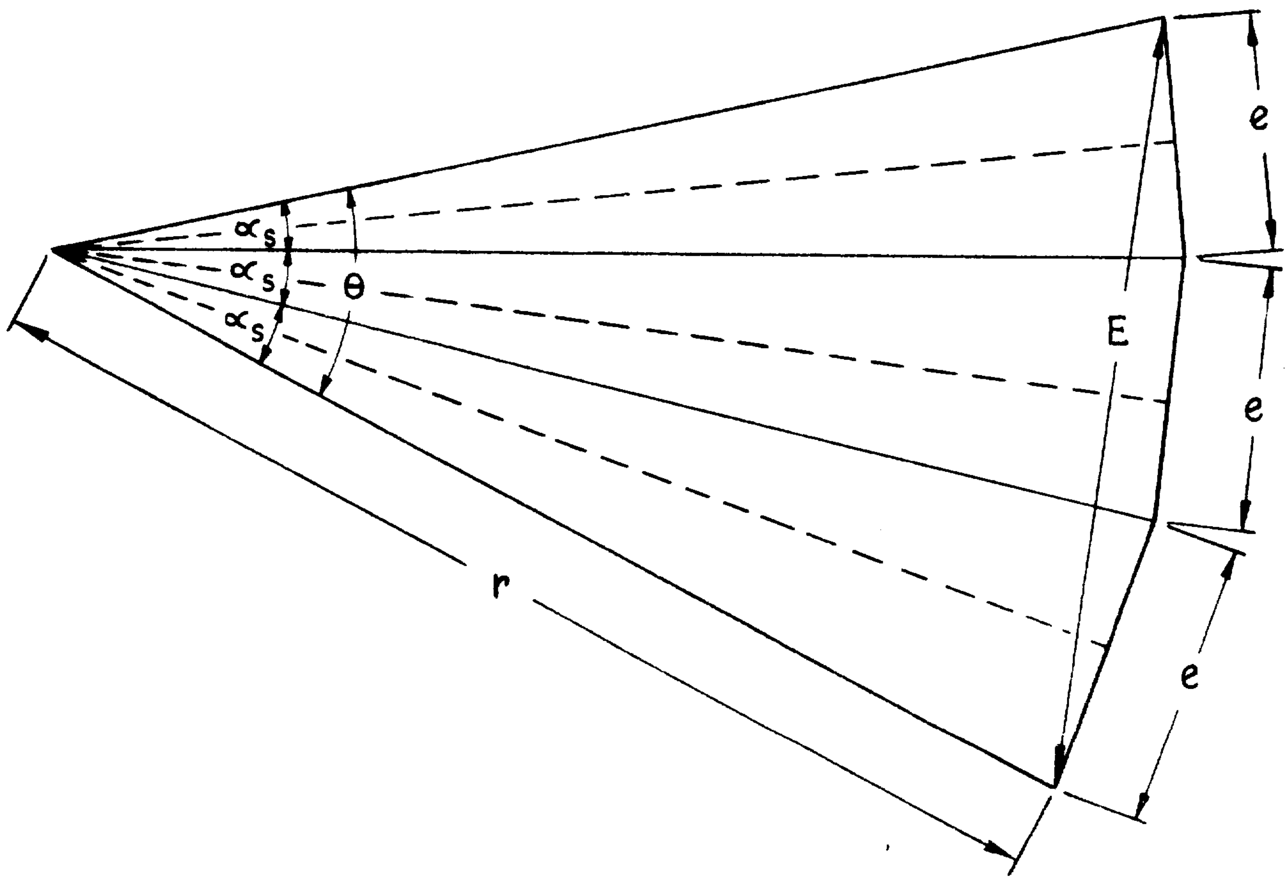
$$\theta = q\,\alpha_s$$

$$\sin \frac{\alpha_s}{2} = \frac{e/2}{r} = \frac{e}{2r}$$

$$r = \frac{e}{2 \sin \frac{\alpha_s}{2}}$$

$$\sin \frac{\theta}{2} = \sin \frac{q\,\alpha_s}{2} = \frac{E}{2r}$$

$$E = 2r \sin \frac{q\,\alpha_s}{2} = 2\left(\frac{e}{2 \sin \frac{\alpha_s}{2}}\right)\sin \frac{q\,\alpha_s}{2} = \frac{e \sin \frac{q\,\alpha_s}{2}}{\sin \frac{\alpha_s}{2}}$$



e
e
e
E
α_s
α_s
α_s
θ
r

$$\text{Thus } K_d = \left(\frac{e \sin \frac{q\alpha_s}{2}}{\sin \frac{\alpha_s}{2}}\right) \div qe = \frac{\sin \frac{q\alpha_s}{2}}{q \sin \frac{\alpha_s}{2}}$$

Since a displacement of α_s between the slots is $n\alpha_s$ for the nth harmonic,

K_{dn} for the nth harmonic is $K_{dn} = \dfrac{\sin \frac{qn\alpha_s}{2}}{q \sin \frac{n\alpha_s}{2}}$

FRACTIONAL SLOT DISTRIBUTION FACTOR

Refer to the slot star shown in Figure 3 of the section titled "Grouping of Fractional Slot Windings" and it will be noted that to determine K_d for a fractional slot winding it is necessary to distinguish between the angle between two slots α_s and the angle between two vectors α_m. This latter angle is the magnetic field angle between the slots of the recurrent group and this angle determines the phase difference between the vectors. The magnetic field angle is $\alpha_m = 180^\circ/Nm$ where N is the same as in "Grouping of Fractional Slot Windings".

It can be seen from the slot star that the fractional slot winding thus behaves like a winding with N slots per phase per pole shifted with respect to each other by the magnetic field angle α_m. Therefore the distribution factor is

$$K_d = \frac{\sin \frac{N\alpha_m}{2}}{N \sin \frac{\alpha_m}{2}}$$

The general effect of distributing a winding is to smooth out the wave form by diminishing the amplitude of the harmonics with respect to the fundamental. The distribution of the armature copper loss is also improved.

The distribution factor of the three phase winding is greater than that of the two phase winding and for this reason the three phase winding is used where there is a free choice of the number of phases. The distribution factor of the single phase winding is much smaller than that of either 3 or 2 phase windings because the winding is distributed over a larger arc.

In general only 2/3 of the slots per pole are used in winding single phase machines. The reason for this can be best shown by an example. Let the number of slots per pole equal 9, and if all slots were wound then $\alpha_s = 180^o/9 = 20^o$, and

$$K_d = \frac{\sin\left(9 \times \frac{20}{2}\right)}{9 \times \sin 10^o} = \frac{1}{1.563} = .640$$

If only 6 slots are wound

$$K_d = \frac{\sin (6 \times 10)}{6 \times \sin 10} = .832$$

Thus, for 9 slots the number of effective turns is only $\frac{9 \times .640}{6 \times .832} = 1.15$ times the number of effective turns obtained when using 6 slots, and therefore by using 50% more copper with its additional 50% more loss, only 15% more voltage has been obtained.

SKEW FACTOR

It can be noted in the table of distribution factors that some harmonics have the same distribution factor as the fundamental. These harmonics are called the slot harmonics and their orders are

$$n = \left[K(2mq)\right] \pm 1 = K\left(\frac{Q}{p/2}\right) \pm 1 \quad \text{where K is an integer}$$

The slot harmonics which correspond to K = 1 (slot harmonics of the first order) are among the most troublesome harmonics in AC machines. Their influence, as well as the influence of other harmonics of higher order, can be reduced by skewing and for this reason stator or rotor slots are sometimes skewed. The skewing also reduces the flux variation in the fringing of the flux at the pole tips due to the slots entering and leaving the polar region. Such a flux variation oftentimes contributes to noise.

Skewing has the same effect as the distribution of a winding over a larger zone because it reduces the interlinkages between the field and stator windings. This distribution factor due to skewing is called the skew factor.

For slots that have a large number of slots per coil group the path of the vectors being added approaches the arc of a circle, and when this happens the distribution factor can be expressed as the ratio of the chord AE to the arc AE and

$$\sin \frac{q \alpha_s}{2} = \frac{1/2 \text{ chord AE}}{R}$$

$$\text{chord AE} = 2R \sin \frac{q \alpha_s}{2}$$

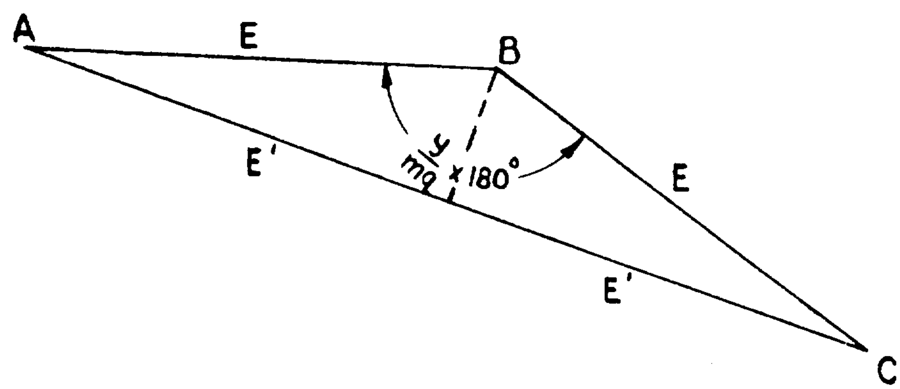
$$\text{arc AE} = Rq \alpha_s$$

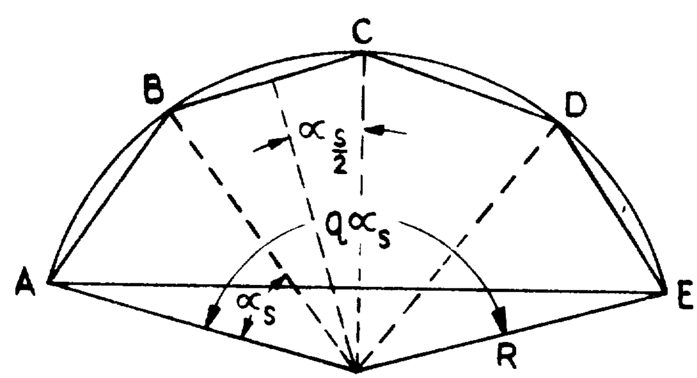
$$K_d = \frac{2R \sin \frac{q \alpha_s}{2}}{Rq \alpha_s} = \frac{\sin \frac{q \alpha_s}{2}}{\frac{q \alpha_s}{2}}$$

If Z is the arc which the coil group occupies per pole and t_p is the pole pitch then

$$\frac{q \alpha_s}{2} = \frac{Z \pi}{t_p 2} \text{ and } K_d = \frac{\sin \frac{Z \pi}{t_p 2}}{\frac{Z \pi}{t_p 2}}$$

Let t_{sk} be the slot skew in inches for a length equal to the core length of the machine and the skew factor K_{sk} is


A
E
B
E'
$\frac{y}{mq} \times 180°$
E
E'
C


C
B
D
$\alpha_{\frac{s}{2}}$
$q\alpha_s$
A
E
α_s
R

$$K_{sk} = \frac{\sin \frac{t_{sk}\pi}{2t_p}}{\frac{t_{sk}}{t_p}\frac{\pi}{2}} \text{ (fundamental) } \& \ K_{nsk} = \frac{\sin n\frac{t_{sk}\pi}{2t_p}}{n\frac{t_{sk}\pi}{2t_p}} \text{ (nth harmonic)}$$

The influence of skewing is nigligible for the fundamental, small for the harmonics of low order, and very considerable for the harmonics of higher order. A skew which is equal to one stator slot pitch makes the influence of the dangerous slot harmonics almost negligible.

PITCH FACTOR

Fractional pitch windings decrease the length of end connections, reduce slot reactance, and provide a means for improving the wave form. They can be used to eliminate any one harmonic from the voltage wave as well as to reduce other harmonics. However, they require a few more turns or a greater flux for the same voltage than a full pitch winding.

Since the two sides of a coil of a fractional pitch winding do not lie under the centers of adjacent poles at the same instant the voltages induced in them are not in phase when considered around the coil. The voltage produced is therefore less than that which would be produced in a full pitch winding. The voltage generated in any single turn is the vector difference of the voltages generated in the two inductors which form the active sides of the turn. If the throw in slots is y, then $(y/mq) \times 180^\circ$ will be the angle of phase difference between the turns and K_p is then derived as follows:

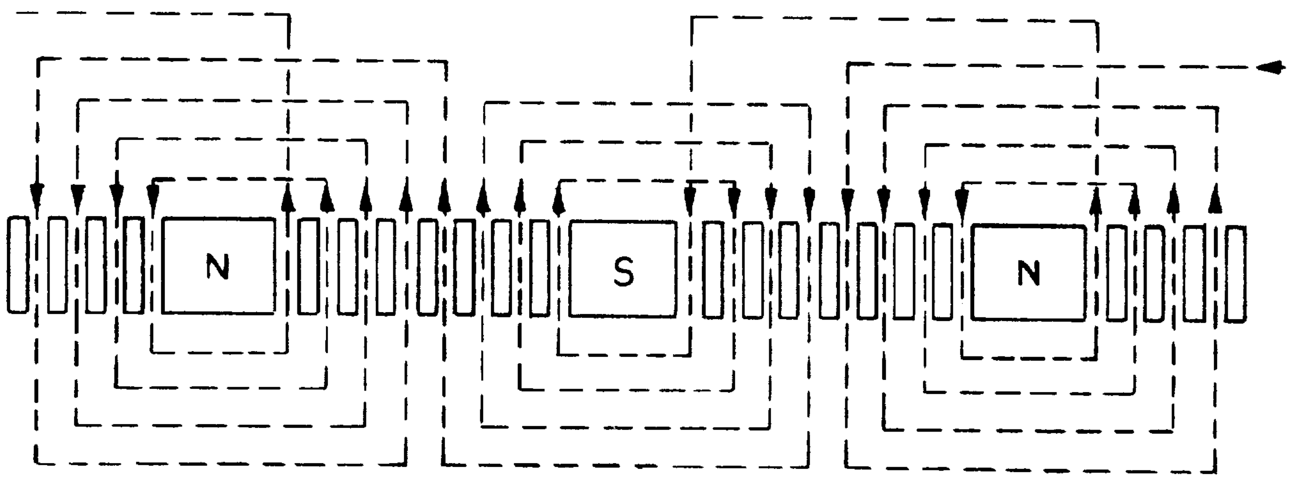
AB = BC = E; since AB = BC, angle C = angle A, and the bisector of $(y/mq) \times 180^\circ$ will be perpendicular to AC and will bisect AC into two equal parts E'; thus

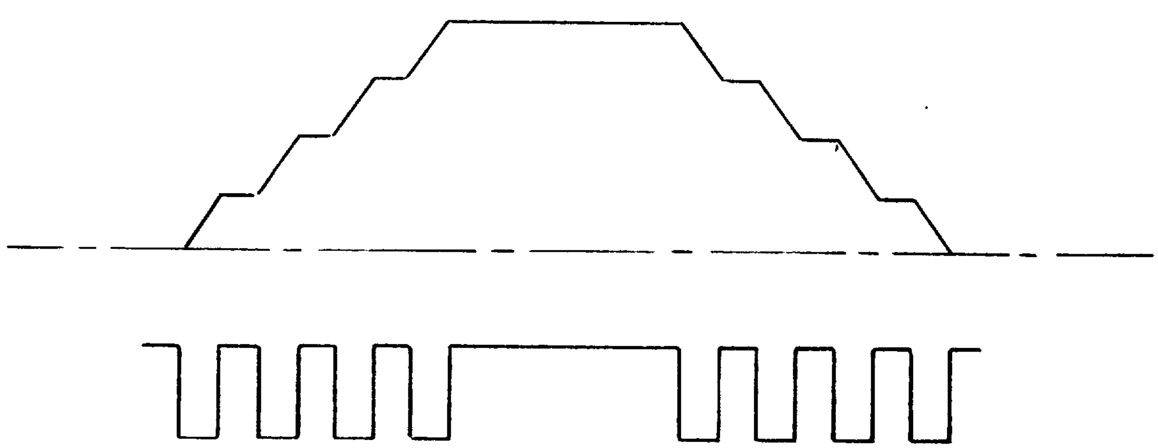
$$K_p = 2E'/2E = E'/E = \sin\left[(y/mq) \times (180^\circ/2)\right] = \sin\left(\frac{y}{mq} \times 90^\circ\right)$$

Since the displacement for any harmonic such as the nth is n times the phase displacement of the fundamental, K_p for any harmonic n is

$$K_p = \sin\left(\frac{ny}{mq} \times 90^{\circ}\right)$$

Any harmonic can be eliminated by choosing a pitch that makes the pitch factor zero for that harmonic. Thus to eliminate the nth harmonic it is only necessary to select a pitch such that $n(y/mq) \times 90^{\circ}$ equals 180°, 360°, 540°, etc. (any multiple of 180°). Eliminating any one harmonic also reduces other harmonics and the fundamental by different amounts. A pitch of 5/6 will give minimum fifth and seventh harmonics and should theoretically give a minimum additional rotor surface loss under load conditions.


N
S
N



Reactances

Machine reactances are sometimes expressed in ohms but are more often given in per cent or in per unit. The per unit system is discussed in Appendix A of Electric Machinery by Fitzgerald and Kingsley, pages 543-546. In our treatment of generators, the per unit values of the various reactances are obtained by dividing the ohmic value of the reactance by the base ohmic value, which is the phase voltage divided by the phase current or Eph/Iph.

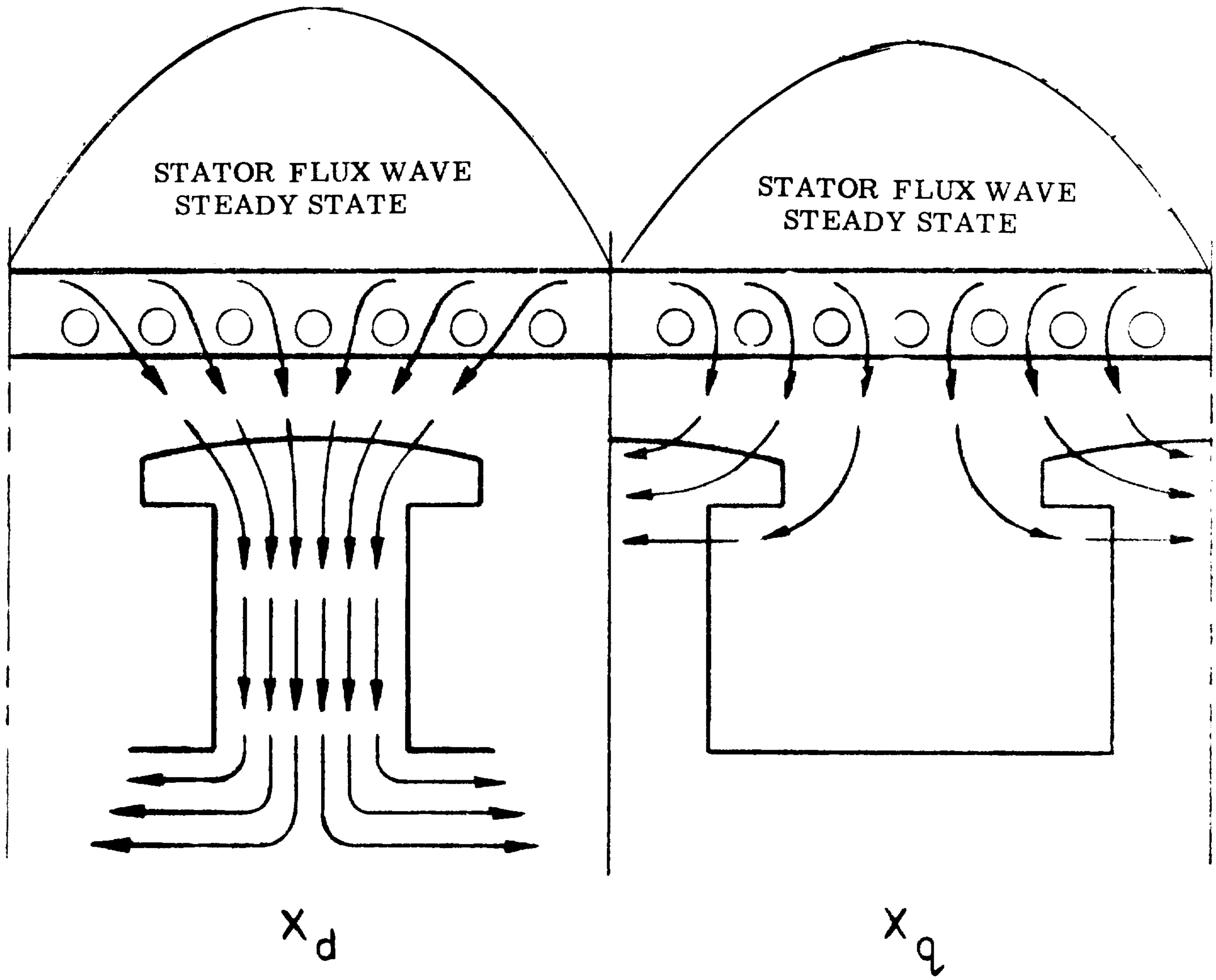
When the generator values are expressed in P. U. (or per cent which is 100 x P. U.), all generators can be compared by the same standards. A 50,000 KW, 60 cycle generator and a 1 KW, 1000 cycle generator look pretty much alike as far as their reactances and per unit values are concerned.

Per unit values can be easily used in system studies and the values are easy to convert to a new base when used in a system involving several machines.

Nearly all of the formulae in this study are arranged to give per cent values. To convert to ohmic values, multiply the per cent value by

$$\frac{Eph}{Iph} \times \frac{1}{100}$$

Any rotating electrical machine has only one zero-sequence reactance and only one negative-sequence reactance but it has several positive-sequence reactances. These positive sequence reactances depend upon the angular position of the rotor and upon whether the positive-sequence currents are steady or are suddenly applied.



When a generator operates on a steady state symmetrical short circuit condition its terminal voltage is zero and its saturation is negligible. Since there is no terminal voltage the net stator linkage must be zero, and thus the stator linkage due to its current acting alone must be exactly equal and opposite in direction to the stator linkage due to the field current acting alone. If the field current were acting alone with the stator open-circuited a certain terminal voltage would exist, and since the armature linkage has the same value as the field linkage, the voltage which must be applied to produce the stator current must be exactly the same as the terminal voltage induced under open circuit.

Therefore the unsaturated synchronous impedance is the ratio of the phase voltage on open circuit resulting from a certain field current to the steady state short circuit stator current resulting from the same field current. Further, since the value of the effective resistance is usually very small in comparison with the reactance it can be neglected, and the impedance and reactance are then equal. Thus

$$X_d = \frac{E\ \text{(open circuit)}}{I\ \text{(short circuit)}}\ \text{ohms}$$

and since the voltage drop due to the stator current is due to the fictituous reactance X_{ad} and the actual reactance $X\ell$

$$X_d = X_{ad} + X\ell$$

<u>Direct Axis Synchronous Reactance X_d</u>

<u>Definition</u> AIEE TEST CODE 503, Para. 1.820

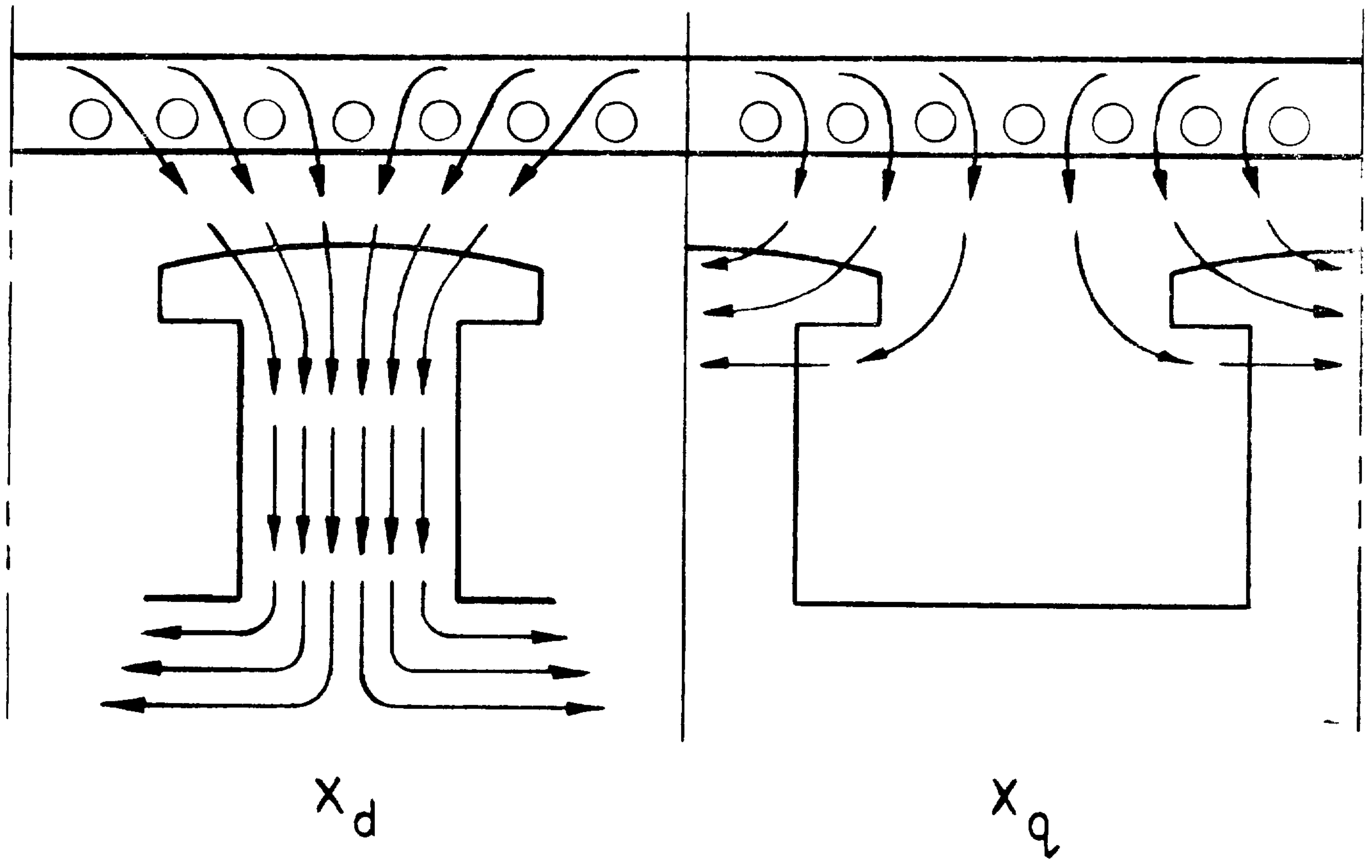
"The direct-axis synchronous reactance is the ratio of the fundamental component of reactive armature voltage due to the fundamental direct-axis component of armature current, to this component of current under steady-state conditions and at rated frequency.

<u>Quadrature Axis Synchronous Reactance X_q</u>

<u>Definition</u> AIEE TEST CODE 583, Para. 1.830

"The quadrature-axis synchronous reactance is the ratio of the fundamental component of reactive armature voltage, due to the fundamental quadrature-axis component of armature current, to this component of current under steady-state conditions and at rated frequency.

FLUX CIRCUIT FOR STEADY STATE CONDITIONS



The above schematics show the circuits for steady-state fluxes in the direct axis and the quadrature axis. The two conditions shown would be obtained when testing for the synchronous reactances, X_d, and X_q. Under steady state loading conditions, the stator flux wave is stationary with respect to the rotor poles, since it is traveling at synchronous speed. Therefore, the damper circuit and the field windings have no effect on the flux.

REACTANCE OF ARMATURE REACTION

Since the shape of the resultant MMF wave is independent of the direction of armature reaction the effect produced by the MMF's of the field and stator windings can be found by treating the two forces as if they each acted alone, and thus the forces may be replaced by the voltages they would cause if acting separately. If this substitution is made the voltage due to armature reaction may be considered as being a voltage drop due to a fictituous reactance X_{ad}, and this is called the reactance of armature reaction. It is not an actual reactance but under steady operating conditions may be considered as such in order to simplify the methods of calculation. It is in phase with the voltage drop due to leakage reactance $I_{ph}X_{\ell}$, and the sum of these two reactances is the synchronous reactance X_d.

If the effect of saturation is neglected the saturation curve becomes a straight line, and then any change in flux with its corresponding change in voltage, produced by any change in MMF is proportional to the change in MMF. Thus, if an unsaturated condition is assumed, the reactance of armature reaction in per unit value can be seen to be the ratio of the MMF of armature reaction to the MMF required by the field to force the flux across the air gap, or

$$X_{ad} = \frac{F_{DM}}{F_g} \quad \text{(percent)}$$

$$\text{Since } F_{DM} = \frac{\sqrt{2}\, n_e C_M I_{ph} K_d}{\pi p} \quad \text{and} \quad F_g = \frac{B_g g_e}{3.19}$$

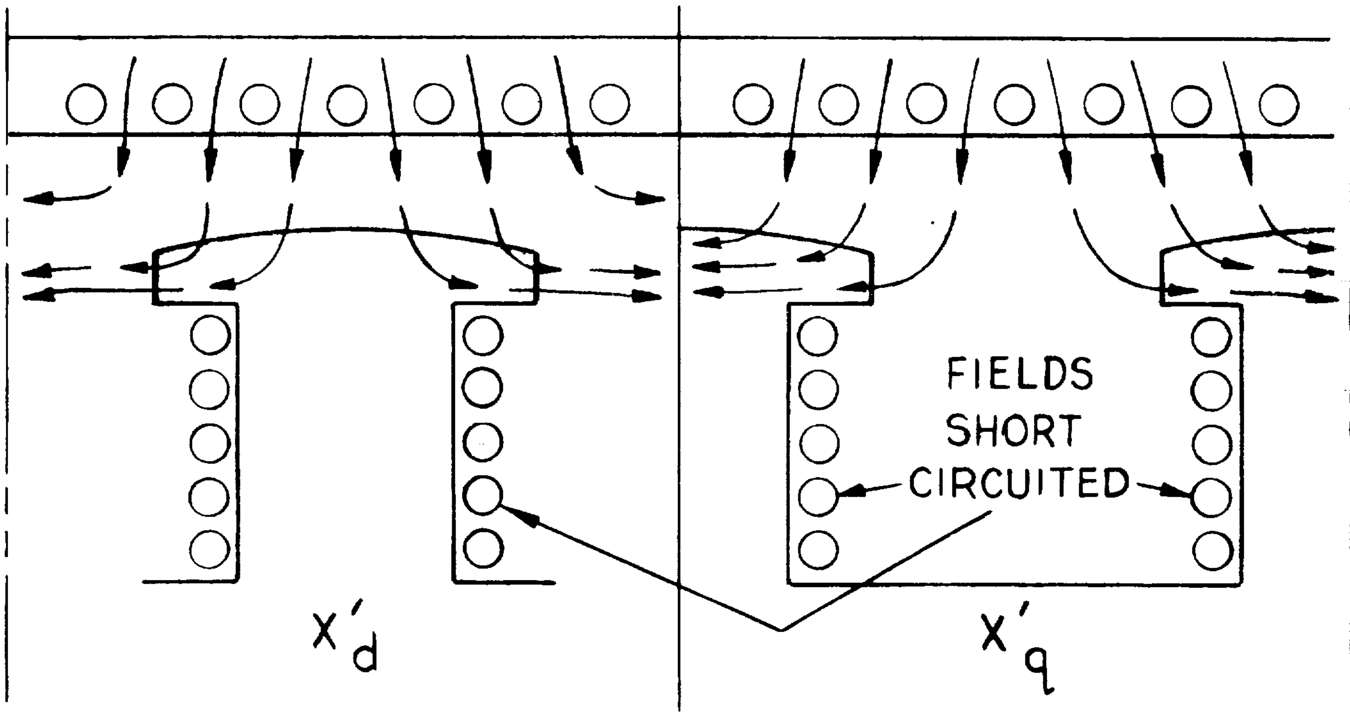
$$X_{ad} = \frac{\sqrt{2}\, n_e C_M I_{ph} K_d \, 3.19}{\pi p B_g g_e} \times \frac{\sqrt{2}\, C_1}{\sqrt{2}\, C_1} = \frac{6.38\, n_e C_M I_{ph} K_d C_1}{\sqrt{2}\, \pi p B_g g_e C_1}$$

$$I_{ph} = \frac{A\pi d}{Q n_s K_p} = \frac{A\pi d}{n_e} \left(\text{from } A = \frac{I_{ph} n_s K_p}{t_s} \text{ and } t_s = \frac{\pi d}{Q} \right)$$

$$\lambda_a = \frac{6.38\,d}{Pg_e} \quad \text{and} \quad \mathbf{X} = \frac{A\,K_d}{\sqrt{2}\,C_1 B_g}$$

$$X_{ad} = \frac{6.38\,dA\,\pi n_e C_M C_1 K_d}{\sqrt{2}\,n_e \pi P g_e B_g C_1} = \mathbf{X}\,\lambda_a C_M C_1$$

FLUX CIRCUIT FOR TRANSIENT CONDITIONS



The two schematics above show the flux circuits for transient conditions in the salient-pole, wound-pole synchronous generator. These conditions obtain when tests are made for X'_d and X'_q or when the stator armature reaction flux wave is changing with respect to the poles.

X'_d Transient Reactance

When armature current is abruptly applied to a synchronous generator it may cause the sudden appearance of an opposing mmf opposite each field pole tending to establish flux through the pole core.

In a laminated salient pole rotor with wound poles, the transient flux is opposed by currents in the field winding. These initial currents decay until only the internal impedance X_d opposes the current flow.

The permeance of the leakage path for the transient flux determines the armature transient current level.

TRANSIENT REACTANCE IN THE STATIONARY-COIL BRUSHLESS GENERATORS

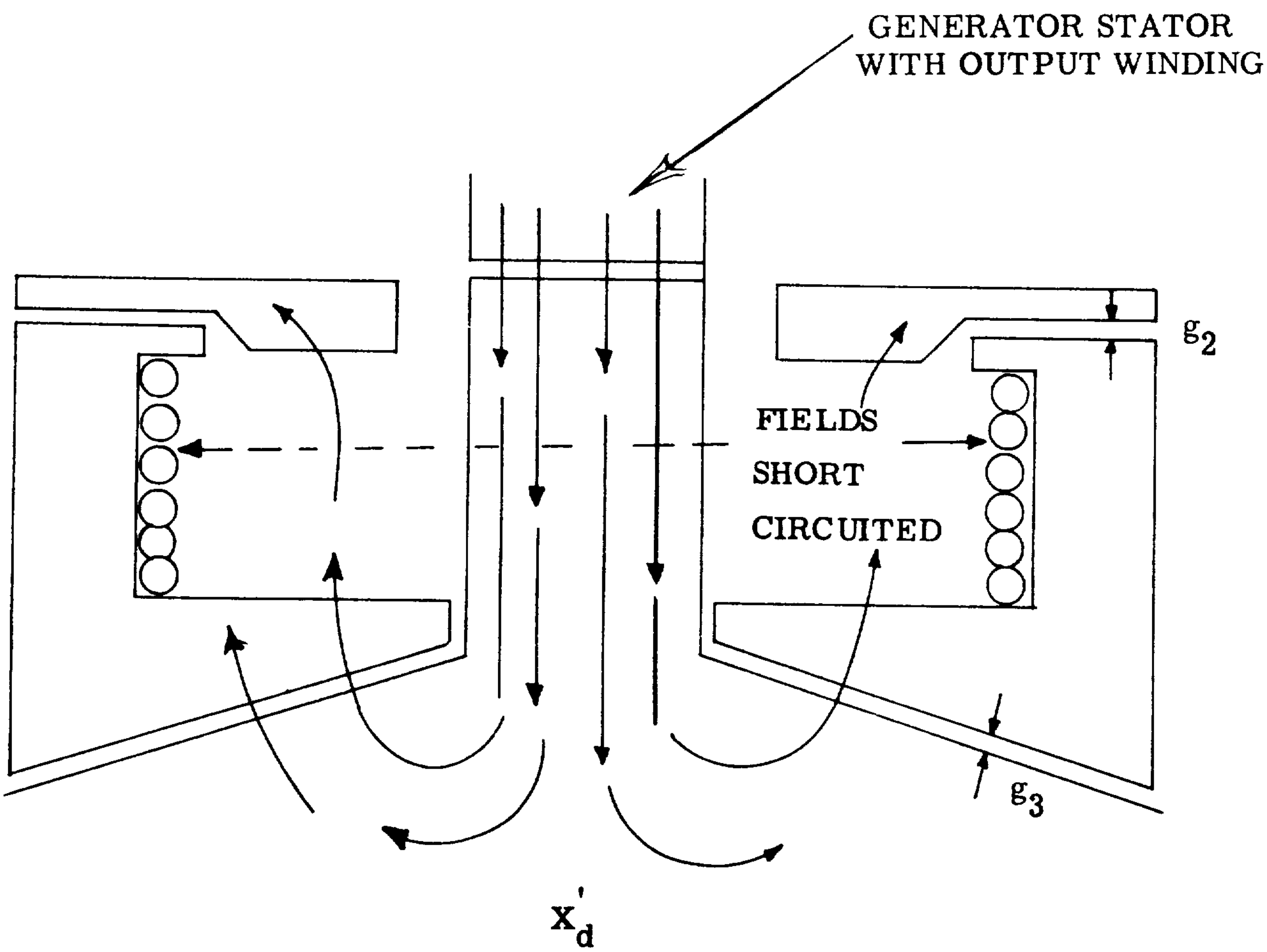
In the solid-rotor or stationary-coil, a-c generators, the field-coil is separated from the main air-gap by two auxiliary air-gaps. The transient flux is prevented from passing through the field coil and is shunted through the field leakage paths. These field leakage paths are large and the resulting transient reactance is large.

The following sketches show the path of the transient flux in a two, inside, stationary-coil, Lundell generator, or Becky-Robinson generator. This sketch is generally representative of the condition existing in any of the stationary-coil generators.

During the first cycle or two of the transient, the flux will be opposed by eddy currents in the rotor surface. These eddy currents reduce the transient reactance by about 15% during these first one or two cycles.

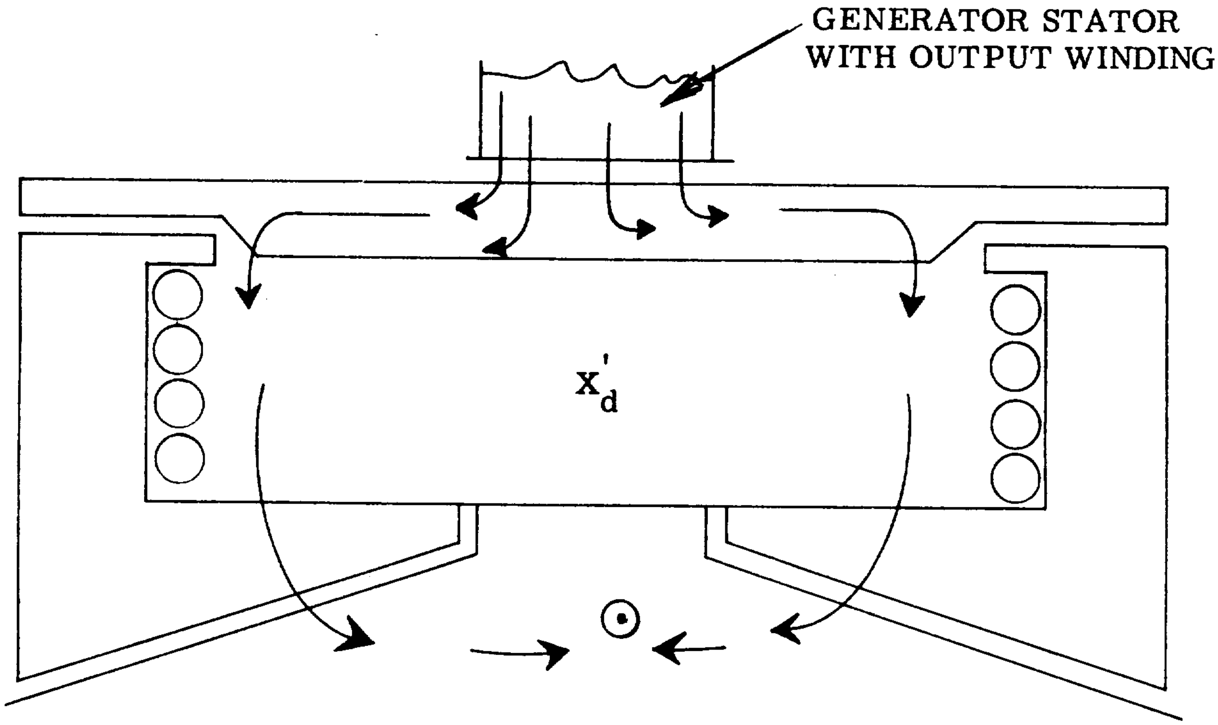
UNSATURATED TRANSIENT REACTANCE -- (X'_{du})

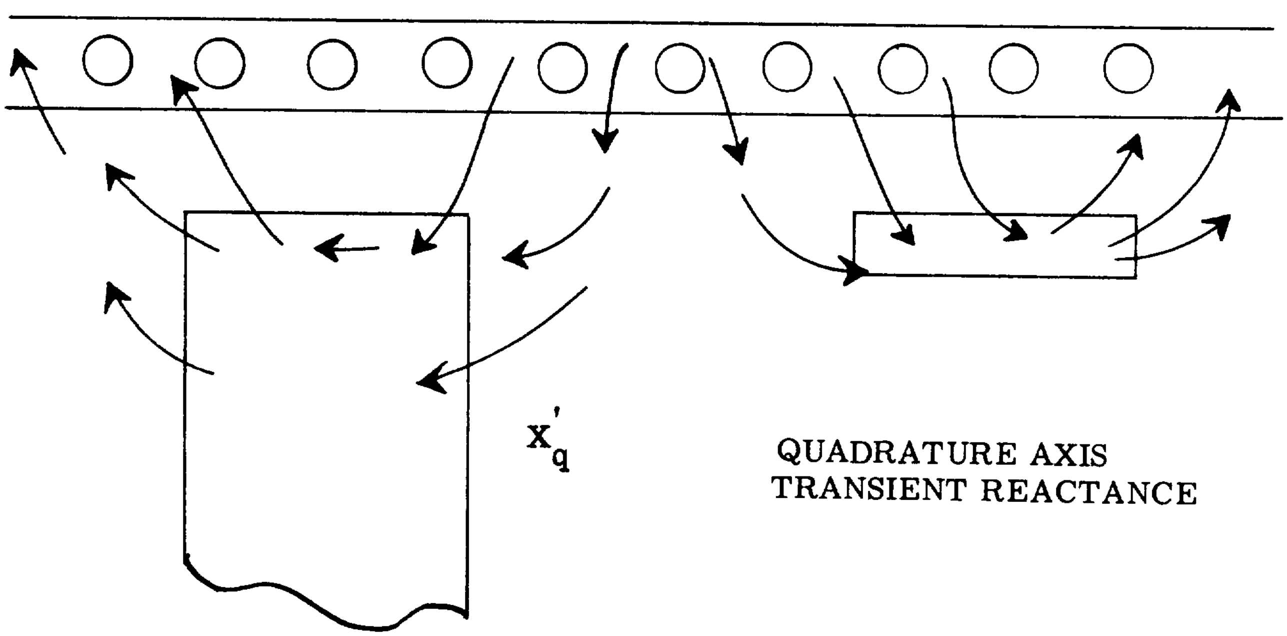
When current is suddenly applied to a generator stator (a step load) there is no flux linkage with the field winding during the first instant, and during that first instant all flux due to the armature mmf is forced through the field coil leakage paths.



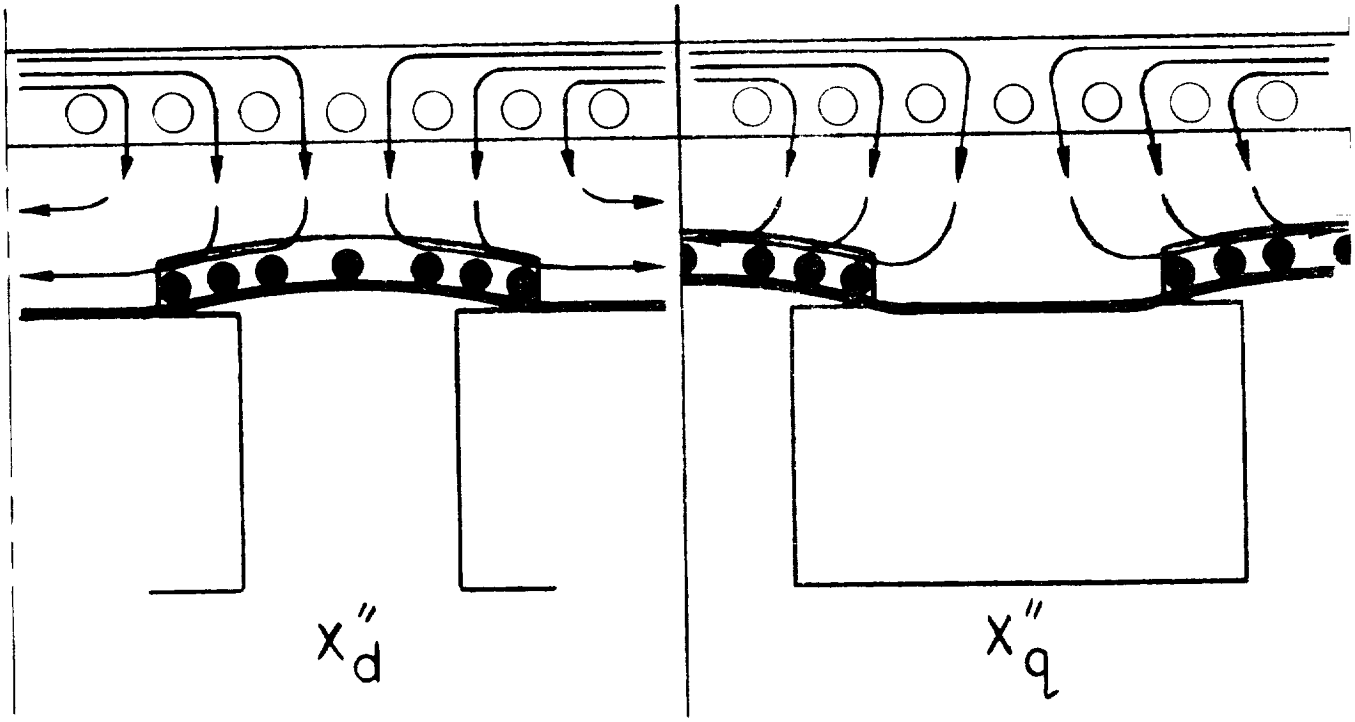
TRANSIENT FLUX IN THE NORTH POLE OF
A BECKY-ROBINSON LUNDELL, A-C GENERATOR

TRANSIENT FLUX IN THE SOUTH POLE OF A BECKY-ROBINSON, LUNDELL A-C GENERATOR





FLUX CIRCUIT FOR SUBTRANSIENT CONDITIONS



X''_d Subtransient Reactance

If armature current is abruptly applied to a synchronous generator which has a damper circuit on the rotor poles, or which generator has a solid pole face, currents will be set up in the damper circuit or pole surface. These currents oppose the change of flux linkages in the rotor circuit and the permeance of the path of the transient leakage flux determines the level of the transient current in the armature.

The subtransient current decays quickly leaving the transient current, which decays less quickly until at last only the steady state current limited by X_d remains.

The subtransient reactance of solid-rotor machines is about 15% lower than the transient reactance of the same machine.

X_2 Negative-Sequence Reactance

Negative sequence currents applied to the stator produce a mmf rating backwards at synchronous speed. With respect to the rotor which is rotating forward at synchronous speed, the negative sequence mmf and flux waves are rotating backwards at twice synchronous speed.

Currents of twice rated frequency are induced in all rotor circuits keeping the flux linkages of those circuits at almost constant zero value. The flux due to the negative sequence armature current is forced into paths of low permeance which do not link any rotor circuits. These paths are the same as for the subtransient flux.

Since the negative-sequence flux wave alternately meets permeances of the two rotor axes corresponding to subtransient reactance X_d'' and X_q'' it is usually calculated as

$$X_2 = \frac{X_d'' - X_q''}{2}$$

the arithmetical mean.

X_0 Zero-Sequence Reactance

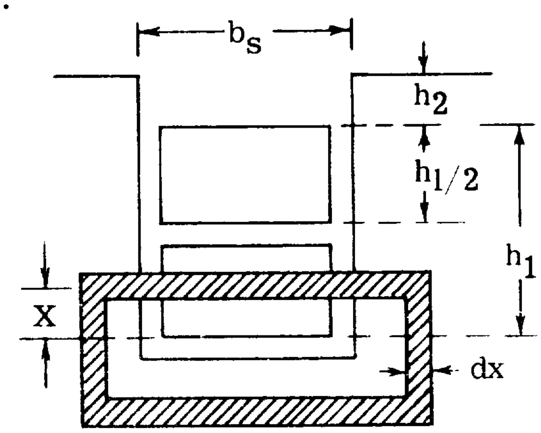
Zero-sequence currents in the armature produce slot-leakage, end-leakage, and differential-leakage fluxes, but not the same leakages as are produced by positive-sequence current. The leakage flux produced is small and X_0 is the smallest of all the reactances; lower than X_d''.

The value of X_0 varies through a wide range and depends upon the coil pitch. It is least for 2/3 pitch.

LEAKAGE REACTANCE

In addition to the demagnetizing action of armature reaction there also exists a voltage drop due to the leakage fluxes. The lines of leakage flux go partly across the slot from one wall to the other (slot leakage), partly from tooth top to tooth top, (tooth tip), partly from phase belt to phase belt (zig zag), and partly in the end windings (end leakage). Each of the leakage fluxes is directly proportional to the current which produces it because its reluctance is principally in air.

Consider first the slot leakage flux. This flux includes all the flux which links the portion of the conductors that are embedded in the iron, but which does not enter the air gap. Assume an integral slot, full pitched winding, and assume that the flux passes directly across the slot. The effect of the notches at the wedge will be neglected and the current density in the conductors will be assumed constant. Also, for simplification, the distance between the top and bottom coil will be assumed negligible.



The flux produced by the element in the bottom of the slot will surround this element. It passes across the slot above the element and returns in the iron below it. The flux will thus encircle part of the coil plus all of the slot above the coil. For the part above the coil the flux will proportion itself equally over the distance $h_{1/2} + h_2$, and since the inductance L equals $\frac{3.19n_s^2 a}{4\ell 10^8}$ the L per slot per inch of core length for this part is:

$$L = \frac{3.19n_s^2 (h_{1/2} + h_2)}{4b_s 10^8}$$

For the inductance of the part of the coil itself consider the element dx enclosing part of the conductor. The L per slot per inch of core length for this part will be equal to $\frac{3.19}{10^8} \sum \frac{N_x^2}{R_x}$ and since $N_x = \frac{x}{h_{1/2}} \quad \frac{n_s}{2}$ and $R_x = \frac{b_s}{dx}$ then

$$L = \frac{3.19}{10^8} \int_o^{L_{1/2}} \frac{x^2 n_s^2 dx}{h_{1/2}^2 \, 4b_s} = \frac{3.19 n_s^2 h_{1/2}^3}{10^8 h_{1/2}^2 4b_s 3} = \frac{3.19 n_s^2}{4b_s 10^8} \text{ x } \frac{h_{1/2}}{3}$$

and the total inductance of the bottom coil side is

$$L_B = \frac{3.19 n_s^2}{4b_s 10^8} \left(h_{1/2} + h_2 + \frac{h_{1/2}}{3} \right) = \frac{3.19 n_s^2}{10^8} \left(\frac{h_{1/2}}{3b_s} + \frac{h_2}{4b_s} \right)$$

In the same manner the inductance of the top coil side will be that due to its own current plus that due to the flux in the part h_2 above the coil and thus:

$$L_T = \frac{3.19 n_s^2}{4b_s 10^8} \left(\frac{h_{1/2}}{3} + h_2 \right) = \frac{3.19 n_s^2}{10^8} \left(\frac{h_{1/2}}{12b_s} + \frac{h_2}{4b_s} \right)$$

Since a full pitched winding has been assumed, the currents of both coil sides will be in phase in all slots and the mutual inductance in the top coil due to the current in the bottom coil will be equal to that in the bottom coil due to the current in the top. Thus L_M in the top coil due to i in the bottom coil will be

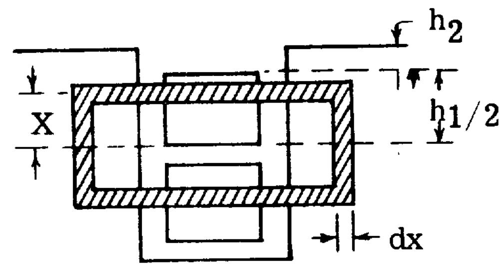
$$L_M = \frac{3.19 n_s^2}{4\ell 10^8} \sum \text{current in the top coil enclosed by the flux from}$$

the bottom.

At the distance x the current enclosed is

$$\left(\frac{x}{h_{1/2}}\right) dx \text{ and } L_M = \frac{3.19n_s^2}{4b_s 10^8 h_{1/2}} \int_o^{h_{1/2}} x\,dx = \frac{3.19n_s^2}{10^8}\left(\frac{h_{1/2}}{8b_s}\right)$$

For the portion above the slot



$$L_M = \frac{3.19n_s^2}{10^8}\left(\frac{h_2}{4b_s}\right)$$

as in the previous cases.

Therefore, since total inductance is $L_T + L_B + 2L_M$ the total inductance per slot per inch of core length is

$$L = \frac{3.19n_s^2}{10^8}\left(\frac{h_{1/2}}{12b_s} + \frac{h_2}{4b_s} + \frac{h_{1/2}}{3b_s} + \frac{h_2}{4b_s} + \frac{2h_{1/2}}{8b_s} + \frac{2h_2}{4b_s}\right) = \frac{3.19n_s^2}{10^8}\left(\frac{2h_{1/2}}{3b_s} + \frac{h_2}{b_s}\right)$$

Since the portion of the slot between the coils has been neglected it can now be included by making $h_{1/2}$ in the above derivation equal to

$\frac{h_1}{2}$ and the formula for L will then be:

$$L = \frac{3.19n_s^2}{10^8}\left(\frac{h_1}{3b_s} + \frac{h_2}{b_s}\right)$$

The tooth tip and zigzag leakage components have been derived by Kilgore with flux plotting methods and these have been determined to be

$$\frac{b_t^2 n_s^2 3.19}{16 t_s g 10^8} \quad \text{and} \quad \frac{.35 b_t n_s^2 3.19}{t_s 10^8}$$

Adding these to the slot leakage portion gives

$$L = \frac{3.19n_s^2}{10^8}\left(\frac{h_1}{3b_s} + \frac{h_2}{b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right)$$

The above derivation has been based upon a full pitched integral slot winding. When the winding is chorded, however, as is usually the case in polyphase machines, the currents in the two coil sides in a certain number of slots will be out of phase and the coefficient of self inductance will be smaller than for the full pitch case. For the slots in which both the bottom and top layer belong to the same phase the conditions are the same as for full pitch. Both coil sides carry currents of the same phase and the phase angle between the currents is zero. In the slots in which the bottom layer and top layer belong to different phases, the phase angle β between the currents is not zero and the mutual inductance between the two layers will be reduced. The reduction factor is equal to $\cos\beta$.

Two reduction factors have to be used: K_{xco} for the slot part in which the conductors lie, and K_{xt} for the part above the conductors. Thus L becomes

$$L = \frac{3.19n_s^2}{10^8}\left[K_{xco}\left(\frac{h_1}{3b_s}\right) + K_{xt}\left(\frac{h_2}{b_s}\right) + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right]$$

The factors K_{xco} and K_{xt} will vary according to the percent pitch and when they are derived they are found to be independent of the number of slots per phase per pole. Hence, since they depend solely upon the percent pitch, they have been combined into a single factor K_x which is reasonably accurate for most machines. It is determined as follows:

$$K_x = \frac{1}{4}\left(\frac{3y}{mq} + 1\right) \quad \text{for three phase machines}$$

$$K_x = \frac{y}{mq} \quad \text{for two phase machines}$$

Therefore the leakage inductance per slot finally becomes

$$L = \frac{3.19n_s^2}{10^8} K_x \left(\frac{h_2}{b_s} + \frac{h_1}{3b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right)$$

and the per unit reactance per phase will be

$$X_s = 2\pi fL \frac{Q\ell}{m} \frac{Iph}{Eph} \qquad \text{where}$$

$$Iph = \frac{A\pi d}{QK_p n_s}$$

$$Eph = \frac{1}{\sqrt{2}} n_s C_1 B_g \ell \frac{\pi dRPM}{60} 10^{-8} \frac{Q}{m} K_p K_d$$

(see total flux derivation)

$$X_s = \frac{2\pi p RPM\, 3.19n_s^2 K_x QA\pi d\sqrt{2}\ 60\ 10^8 m\ell}{m\, 120\ 10^8 QK_p n_s n_s C_1 B_g \ell\pi dRPMQK_p K_d}\left(\frac{h_2}{b_s} + \frac{h_1}{3b_s} + \frac{b_t}{16t_s g} + \frac{.35b_t}{t_s}\right)\frac{\sqrt{2}}{\sqrt{2}}$$

Substituting Q = pmq

$$X_s = \frac{20pAmK_x}{m^2 qpK_p^2 C_1 B_g K_d \sqrt{2}}\left(\frac{h_2}{b_s} + \frac{h_1}{3b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right)\frac{K_d}{K_d}$$

$$\text{Let } C_x = \frac{K_x}{K_p^2 K_d^2} \qquad \text{and since } \mathbf{X} = \frac{AK_d}{\sqrt{2}\, C_1 B_g}$$

$$X_s = \mathbf{X} C_x \frac{20}{mq}\left(\frac{h_2}{b_s} + \frac{h_1}{3b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right)$$

Many attempts have been made to determine accurate formulas for the end winding leakage reactance, but the one that appears to be most promising for small machines is the one proposed by E. C. Barnes in AIEE Volume 70-1951. Expressed in per cent notation this formula will be:

$$\% X_E = 6.28 f \left(\frac{n_s}{C}\right)^2 q^2 K_p^2 \, pm \left[\frac{\emptyset_E L_E}{2n}\right] \frac{Iph}{Eph} \, K_E 10^{-6}$$

where $\frac{\emptyset_E L_E}{2n}$ is proportional to the pole pitch and is taken from Graph No. 1 and K_E is proportional to the ratio of the calculated L_E to the L_E of Graph No. 1.

$$K_E = \sqrt{\frac{\text{calculated } L_E}{L_E \text{ from Graph \#1}}} \qquad \text{(for d below 8" diameter)}$$

$$\text{and } K_E = \frac{\text{calculated } L_E}{L_E \text{ from Graph \#1}} \qquad \text{(for d above 8" diameter)}$$

$$\text{Since } Iph = \frac{CA\pi d}{QK_p n_s} \quad \text{and } Eph = \frac{n_s C_1 B_g \ell \pi d \, RPM \, QK_p K_d}{\sqrt{2}\, C 60 M 10^8}$$

$$\% X_E = 6.28 f \left(\frac{n_s}{C}\right)^2 q^2 K_p pm \left[\frac{\emptyset_E L_E}{2n}\right] K_E \frac{\sqrt{2}}{\sqrt{2}} \left[\frac{CA\pi d}{QK_p n_s} \; \frac{\sqrt{2}\; 60\; 10^8 mc}{n_s C_1 B_g \ell \pi d \, RPM \, QK_p K_d \, 10^6}\right]$$

Multiplying by $\frac{K_d}{K_d}$ and substituting $f = \frac{P(RPM)}{2 \times 60}$; $X = \frac{100AK_d}{\sqrt{2} C_1 B_g}$; $q = \frac{Q}{pm}$

gives $$\% X_E = X \frac{6.28_p RPM}{2 \times 60} \; \frac{Q^2 pm}{p^2 m^2} \left[\frac{Q_E L_E}{2n}\right] K_E \frac{2 \times 60 m}{Q^2 \ell RPM K_d^2}$$

$$\% X_E = X \frac{6.28}{\ell K_d^2} \left[\frac{Q_E L_E}{2n}\right] K_E$$

POTIER REACTANCE

The terminal voltage of an alternator under load differs from its open circuit voltage at the same field excitation. This difference is due to a voltage drop through the armature caused by leakage reactance, armature effective resistance, and armature reaction. The relative importance of the three factors depends upon the power factor of the load. With a reactive load at zero power factor the decrease in the terminal voltage is due almost entirely to the armature reaction and the armature leakage reactance. Under this condition the effective resistance drop is in quadrature with the terminal voltage, and since it is small in magnitude, it has little influence on the change in the terminal voltage caused by a change in load. Likewise, the resultant field F_{NL} is almost exactly equal to the algebraic difference between F_{NL} and F_{DM}, and the terminal voltage E is nearly equal to the algebraic difference between E_g and IphX. Under these conditions the armature reaction subtracts almost directly from the impressed field and the armature leakage reactance drop subtracts almost directly from the generated voltage. It follows from this that if an open circuit characteristic OB, and a curve CD are plotted as in Figure 14, showing the variation in the terminal voltage with excitation for the condition of constant stator current at a reactive power factor of zero, the two curves are so related that any two points, as E and F, which correspond to the same degree of saturation and consequently to the same generated voltage, are displaced from each other horizontally by an amount equal to the armature reaction and vertically by an amount equal to the leakage reactance drop.

GF represents the armature reaction in equivalent field amperes and GE represents the leakage reactance drop in volts. The armature leakage reactance per phase for a Y connected generator is thus $X = {}^{EG}/\sqrt{3}\,I$ and this reactance is called the Potier reactance. The triangle EJF is known as the Potier Triangle.

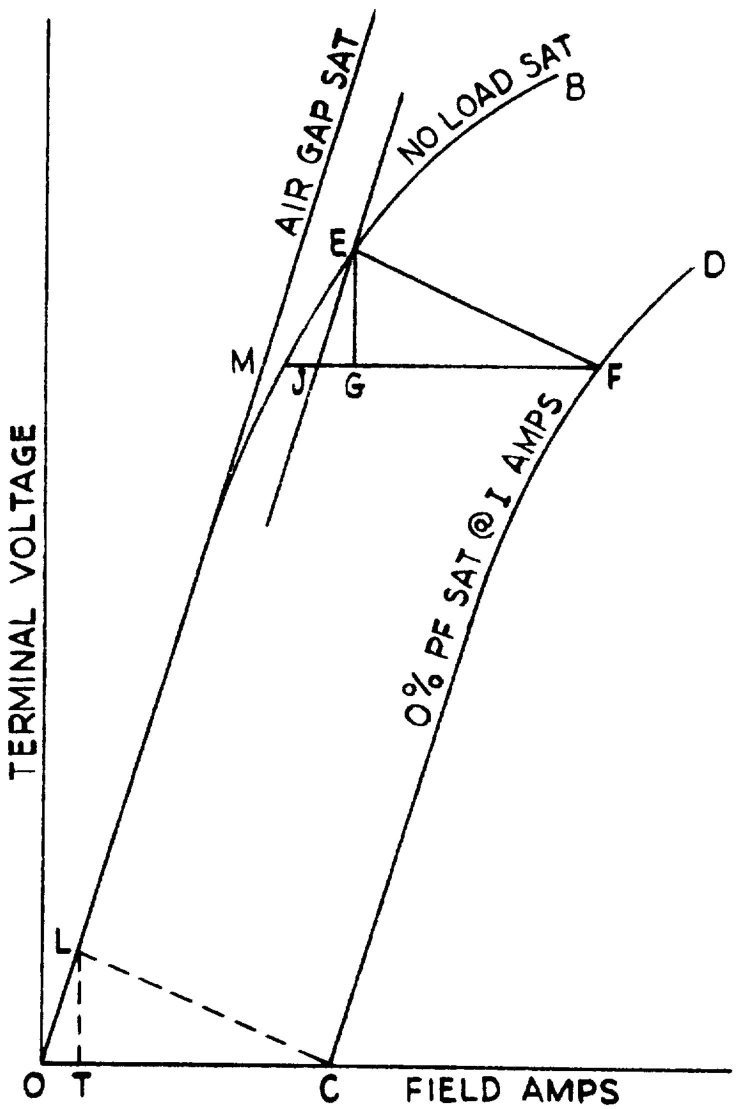
If the leakage reactance is constant and the increase in field current necessary to balance a given number of ampere turns of armature reaction is independent of the saturation of the magnetic circuit, Potier triangles drawn between the open circuit saturation curve and the zero power factor curve at points corresponding to different degrees of saturation would be identical. Under these conditions the zero power factor curve would have the same shape as the open circuit saturation curve but would be displaced from the open circuit curve by a distance equal to the length of the hypotenuse of the Potier triangle. Actually, the field pole leakage increases somewhat with an increase in saturation, and for this reason the number of field ampere turns which are necessary to balance a fixed number of ampere turns of armature reaction is not quite constant. In spite of this change in field pole leakage, the curves have nearly enough the same shape for practical purposes and are assumed to have the same shape when determining generator performance.

In order to make use of the Potier method to construct a zero power factor curve it is necessary to locate two points on the Potier triangle. Figure 14 shows how the method is applied. A triangle OCL is constructed with OC equal to the amperes corresponding to short circuit ampere turns ($F_{sc} = X_d F_g$). The altitude LT is made equal to IX_{pl} where Potier's reactance is calculated by a partly empirical method and

$$Xp = X\ell + \left[\frac{F_{TR} + F_{CR}}{F_{TR} + F_{CR} + F_T + F_C}\right] X_{FS}$$

$$X_{FS} = \left(\frac{\lambda rs}{\frac{2d}{Pg_e} + \lambda rs}\right) X_d$$

As the point L of the triangle is moved along the no load saturation curve, point C traces the zero power factor saturation curve.



AIR GAP SAT
NO LOAD SAT
B
E
D
M
J
G
F
0% PF SAT @ I AMPS
TERMINAL VOLTAGE
L
O
T
C
FIELD AMPS

FIGURE 14

TRANSIENT AND SUBTRANSIENT REACTANCES AND TIME CONSTANTS

Figure 9 shows the short circuit current in one phase of a three phase alternator that has had all three phases shorted when operating at no load. The line ef drawn midway between the two sides of the envelope is called the direct current component and has different magnitudes in the three phases. The envelope of the alternating component is redrawn in Figure 10 with its axis horizontal, i.e., with the direct current component eliminated. The alternating components are the same in all three phases. When an alternating voltage is short circuited through an inductance and a resistance in series, the short circuit current will consist of two components. These components are the unidirectional or DC component which decreases logarithmically to zero, and an alternating component which is fixed by the voltage, the resistance, and the reactance of the circuit, and is constant when the resistance and reactance are constant.

In the short circuited generator the reactance is not constant until the condition equivalent to synchronous reactance is reached. When a sudden change occurs in the stator current the armature reactance is no longer constant, and under this condition voltages are induced by the changing armature reaction in the field winding, and in any other closed windings on the field structure. As the stator current builds up the voltages of the field structure will build up simultaneously, tending to maintain constant the total number of ampere turns acting on the magnetic circuit. These voltages cause transient currents in these parts.

In a polyphase generator the alternating components of the short circuit stator currents produce armature reaction which is fixed in direction with respect to the poles but decreases from an initial value to a final value fixed by the steady state short circuit currents. To balance this increase in armature reaction there must be an increase in the field current. This increase in field current is in the same direction as the initial field current since the armature reaction caused by lagging currents is demagnetizing. The change in field current decreases and becomes zero, when steady state conditions are reached.

The D.C. components in the stator currents produce a resultant MMF which is fixed with respect to the stator but has fundamental frequency with respect to the field. To balance this the field current must contain an alternating component of fundamental frequency. This alternating component in the field current produces an MMF of fundamental frequency in the air gap which is fixed in direction with respect to the field poles. This MMF can be resolved into two oppositely rotating components, each of which rotates at synchronous speed with respect to the stator. The component which rotates in the direction of the rotor balances the the stator MMF caused by the D.C. components in the stator currents. The oppositely rotating component rotates at double synchronous speed with respect to the stator winding and must be balanced by second harmonic components in the transient stator currents. All except the fundamental alternating components decrease to zero when steady state conditions have been reached and the fundamental alternating components become the steady state short circuit currents.

Consider the elementary generator shown in Figure 11. The stator winding is open and the rotor winding is excited by a D.C. current of magnitude I_f. At the time $t = 0$, when the axes of both windings are perpendicular to each other, the stator winding is suddenly short circuited. As stated previously, the total flux interlinked with each winding under this condition will remain constant. Thus, the total flux interlinked with the field winding at $t = 0$ will consist of two parts; one part going through the path of the main flux, and the other part going through the leakage path of the rotor. The total flux interlinked with the armature at $t = 0$ is zero.

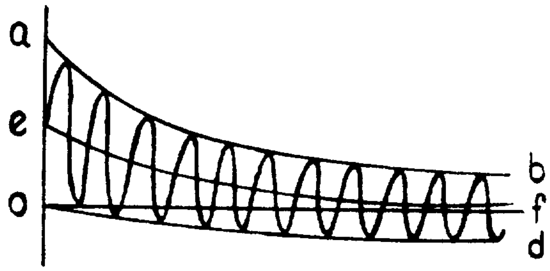


FIGURE 9

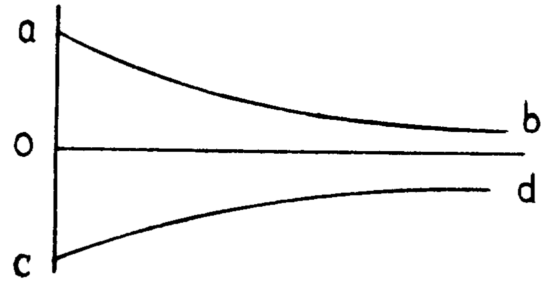


FIGURE 10

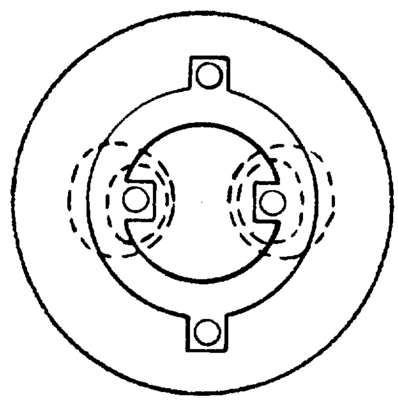


FIGURE 11

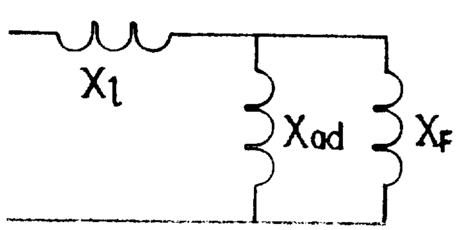


FIGURE 12

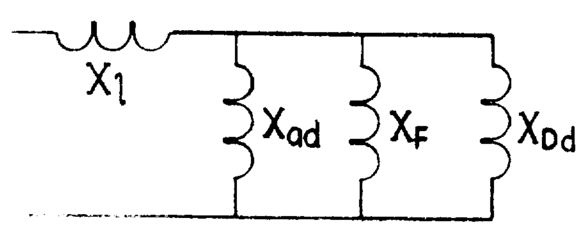


FIGURE 13

During the time t the rotor moves through an angle a = wt and this produces a current i_a in the stator winding and also forces a current i_f to flow in the field winding in order to sustain the field flux interlinkage. The transient currents i_a and i_f are determined by the angle a as well as the leakage fluxes of both windings and they become a maximum when a = $\pi/2$, a quarter period after the short circuit occurred.

It can be shown that the maximum transient stator current is determined by the equivalent circuit of Figure 12, and the reactance that corresponds to this circuit is the direct axis unsaturated transient reactance, X'_{du}. The field reactance, X_F, is given in Kilgore's paper as

$$X_F = X \frac{4}{\pi} C_M^2 \lambda F$$

and therefore the unsaturated transient reactance becomes

$$X'_{du} = X\ell + X_F \left(\frac{X_{ad}}{X_F + X_{ad}} \right)$$

The saturated transient reactance has been determined empirically and is approximately 88% of the unsaturated value.

In the determination of the transient reactance only the field winding of the rotor was considered. If there is a damper winding in the poles, or if eddy currents are possible in the rotor iron, subtransient currents similar to the transient currents of the field winding are induced in these circuits. These circuits will support the field winding for a few cycles and therefore they have to be considered as acting in parallel with the field winding. The equivalent circuit for this case is shown in Figure 13. X_{Dd} is the leakage reactance of the damper winding and eddy current circuits together in the direct axis, and per Kilgore's paper

$$X_{Dd} = X \lambda_{Dd}$$

where $$X_{Dd} = \frac{3.19p}{d}\left[g + \delta_d + h_{r2}\right]$$

δ is a depth of penetration factor and varies as $\sqrt{\frac{1}{f}}$. It is equal to 1.2 at 60 cycles and $\left(\sqrt{\frac{60}{400}}\right)(1.2)$ at 400 cycles. The subtransient reactance is therefore

$$X''_d = X\ell + X_{Dd}$$

The rate of decrease of the transient and subtransient currents will be determined by the time constants of the windings involved. The damper winding and eddy current circuits have much larger ratios of resistance to leakage reactance than the field winding and therefore their influence will be much shorter in duration than that of the field winding. As a matter of fact, the damper winding and eddy current circuits influence the currents only during the first few cycles. The field winding determines the decrease of the amplitudes for a much longer time. The change of the amplitudes during the short circuit period is such that the amplitudes are determined first by the subtransient reactance X''_d, then by the transient reactance X'_d, and finally by the synchronous reactance X_d.

The total self inductance of the field winding is

$$L_f = \frac{N_f^2 p \ell_r}{10^8}\left[C_F\left(3.19\,\frac{t_p}{g_e}\right) + \lambda_F\right]$$

where C_f is the ratio of the interlinkages of the field with its own flux to the maximum interlinkages that would be produced with a uniform gap and a concentrated field winding.

The time constant is the time in seconds required for the particular component to decay to 36.8% of its initial value. The time constant T'_{do} is the time constant of the field winding with the armature circuit open and with negligible external resistance and inductance in the field circuit. Therefore, the open circuit time constant is

$$T'_{do} = \frac{L_f}{R_f}$$

The armature time constant is the time constant of the DC component and is

$$T_a = \frac{X_2}{2\pi f r_a} \qquad \text{where } r_a = \frac{\text{stator } I^2R \text{ (KW)}}{\text{rated KVA}}$$

The transient time constant T'_d is the time constant of the transient reactance component of the alternating wave and with good approximation is

$$T'_d = \frac{X'_d}{X_d} T'_{do}$$

The subtransient time constant T''_d is the time constant of the subtransient reactance component of the alternating wave and is approximately .005 second for 400 cycle machines. (from tests of 60 cycle machines $T''_d \approx .035$ second or 2.1 cycles).

Resistances

Positive Sequence Resistance r_1

The positive sequence resistance of an a-c machine is its a-c armature resistance r which is greater than the d-c armature resistance r_a because of non-uniform current density and local iron loss. r_1 is usually disregarded in system studies except in the case of a 3 phase short circuit near the generator terminals.

Zero-Sequence Resistance r_0

This resistance is small and is usually neglected unless a resistor is used in the neutral of a wye connected machine.

It is the sum of the d-c resistance of the three places (in a 3 phase machine). If a neutral resistor is used, add 3 x the resistor also.

Negative Sequence Resistance r_2

The negative sequence power input to the armature supplies 1/2 of the copper losses of the rotor circuits. The other 1/2 of rotor copper losses are supplied mechanically.

The negative sequence resistance depends upon the resistance of the damper circuit if there is one. It is equal to 1/2 the rotor damper circuit resistance plus the stator resistance

$$r_2 = R_s + \frac{1}{2} R_r$$

GENERATOR VOLTAGE AND OUTPUT EQUATIONS

To begin a generator design when there is no required envelope or other size limitation, time can be saved by using an output formula that relates rotor size to output kva. The output equation is given here and then developed from the relation $E = N_c \ell v B_{max} 10^{-8}$

$$\text{Output kva} = \frac{d_r^2 \ell \text{ (RPM) A Bg}}{90 \times 10^7}$$

where d_r = rotor diameter which is for practical purposes the same as the stator I. D. (inches)

ℓ = stator length in inches

A = ampere wires/inch of bore periphery

Bg = gap density in kilolines/in^2

All electromagnetic generators convert mechanical energy to electrical energy through a change of flux linking the conductors of the output winding.

The voltage generated in a single conductor is -

$$E = \ell \, v \, B_{max} \, 10^{-8}$$

$$e/\text{coil} = 2 \text{ Emax sin wt Kp}$$

$$\text{Eph} = \frac{e_{rms}}{\text{Coil}} \times \frac{\text{Coils in Series}}{\text{phase}} \times K_d$$

$$= \frac{e_{rms}}{\text{Coil}} \times \frac{\text{Total Slots } K_d}{\text{Phases x Parallels}}$$

$$= \frac{2 \ell v B \max 10^{-8}}{\sqrt{2}} \times \frac{QK_d}{mc} \times N_s$$

$(N_s$ = Conductors/Slot)

$$\phi_T = Bg\, \pi\, d_r\, \ell$$

$$B_{max} \text{ Fundamental} = C_1\, Bg$$

$$\ell v\, B_{max} \text{ Fund} = C_1\, \phi_T \times \frac{RPM}{60}$$

$$E \text{ phase} = C_1\, \phi_T \frac{RPM}{60} \times \frac{K_p\, N_s\, Q\, K_d\, 10^{-8}}{\sqrt{2}\, mc}$$

$$= \frac{C_1\, \phi_t \frac{RPM}{60}\, Ne\, K_d \times 10^{-8}}{\sqrt{2} m}$$

(Ne = total effective conductors in the stator $= \frac{Q\, N_s\, K_p}{C}$)

$$\phi_T = \frac{60\, Eph}{RPM\, Ne} \times \frac{\sqrt{2}\, m}{C_1\, K_d} = \frac{60\, E_{LL}\, \sqrt{2}\, m\, 10^8}{RPM\, Ne\, C_1\, K_d \frac{E_{LL}}{Eph}}$$

$$C_w = \text{Winding Constant} = \frac{C_1\, K_d \frac{E_{LL}}{Eph}}{\sqrt{2}\, m}$$

$$\phi_T = \frac{60 \times 10^5 \times E_{LL}}{RPM\, C_w\, Ne}$$

C_w for 3 phase $= .39\, C_1$

C_w for 2 phase $(90^o) = .319\, C_1$

C_w for 3 phase $= .225\, C_1$

The derived voltage equation can be found in the AIEE Paper No. 50-201 dated August, 1950, "Design Calculations for A. C. Generators" by David Ginsberg,

$$E_{LL} = \frac{\phi_T (RPM) C_w N_e}{60\ (10^5)}$$

Where ϕ_T = Hypothetical total flux in the air gap of the machine (in kilolines). This is the maximum density over the pole times the area of the stator bore.

N_e = Total effective conductors in the machine.

RPM = Revolutions per minute.

C_w = Winding Constant

$$= \frac{E_{LL}}{m\, E_{ph}} \times \frac{C_1 K_d}{\sqrt{2}} = .39\ C_1 \text{ for a 3 phase machine}$$

Where m = No. of phases

K_d = Distribution Factor = .955

C_1 = Ratio $\frac{\text{Maximum Fundamental}}{\text{Actual Maximum}}$ of the flux wave. This value is 1.0 for a sine wave and a sine wave is assumed in the formula.

Then $$KVA = \frac{I_L E_{LL} \sqrt{3}}{10^{-3}}$$

$$KVA = \left(\frac{\phi_T\, RPM\, C_w N_e}{60 \times 10^5}\right) \frac{I \sqrt{3}}{\times 10^{-3}}$$

$$\phi_T = B_{gap} \times \text{Area Gap}$$

$$I = \frac{A \pi d}{N_e} \quad \text{since } A = \frac{N_e I_{ph}}{\pi d} = \text{ampere wires per inch of stator bore periphery}$$

$$KVA = \frac{B_g(\pi d\, l_c)RPM(.39C_1)N_e \quad \sqrt{3}\, A\, \pi d}{60 \times 10^8 N_e}$$

$$= \frac{B_g\, 9.85 d^2 l_c\, RPM\ .39\, C_1\, A\ \sqrt{3}}{60 \times 10^8}$$

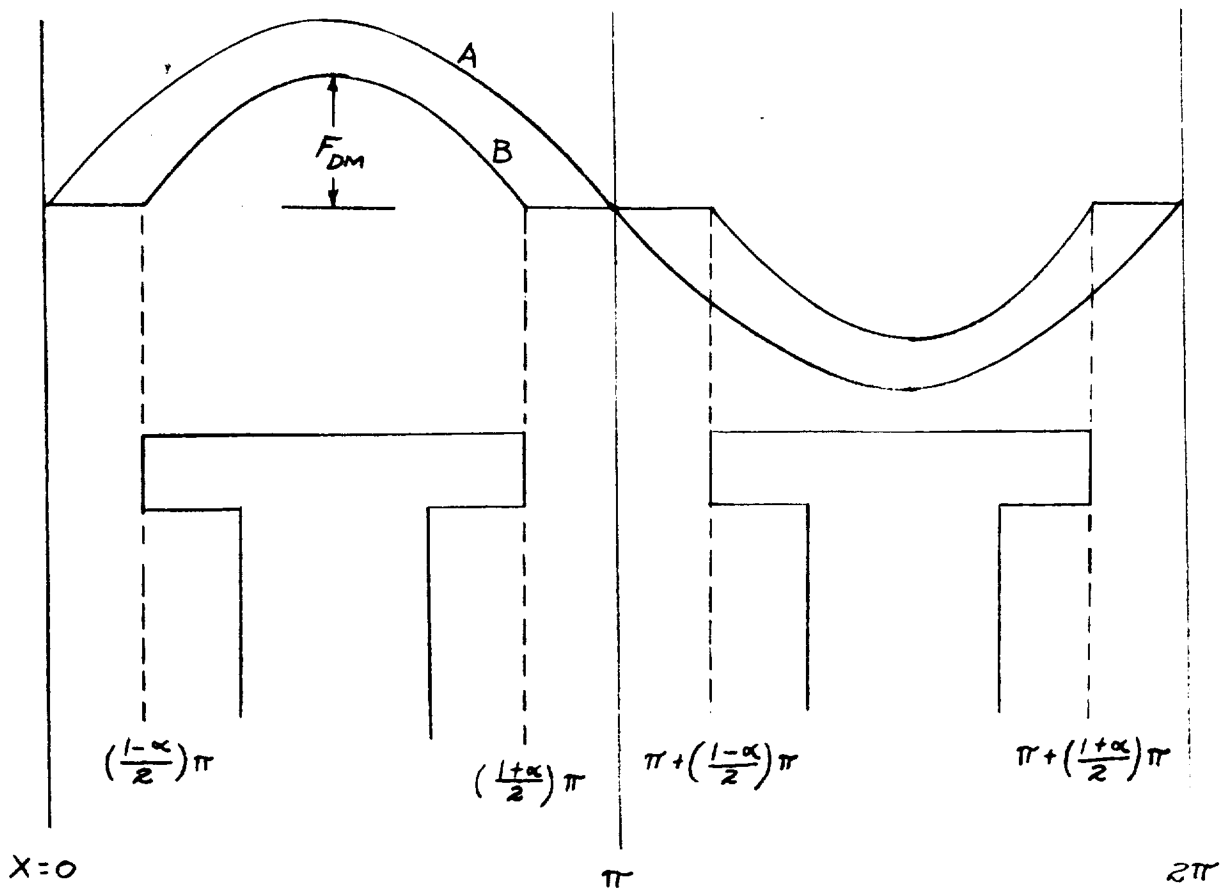
$$KVA = \frac{B_g(d^2 l_c)(RPM)A}{90 \times 10^7}$$ The basic equation.

If a pole embrace is used that gives other than $C_1 = 1.0$ (or if the maximum of the fundamental flux wave is not equal to the maximum of the actual flux wave), the KVA formula should be multiplied by C_1.

Note: Liwschitz-Garik and Whipple in "Electric Machinery" Vol. 2, appendix 8, pp 553-557 derived an equivalent formula for either motors or generators.

Cm

DIRECT AXIS COMPONENT OF ARMATURE REACTION



When the air gap under the pole is constant the field produced by the direct axis armature reaction MMF wave A will have the approximate shape B insofar as its reaction on the field pole is concerned. Since this MMF produces very little demagnetizing effect in the interpolar region it is sufficient to consider only the fundamental of the effective part of the MMF curve (the part which lies under the pole). The amplitude of this fundamental is given by the equation

$$A_1 = \frac{1}{\pi}\int_0^{2\pi} f(x) \sin x \, dx$$

If the ratio of the pole arc to the pole pitch is designated as α then

$f(x) = 0$ from $x = 0$ to $x = \left(\frac{1-\alpha}{2}\right)\pi$

$f(x) = F_{DM}\ \sin x$ from $\left(\frac{1-\alpha}{2}\right)\pi$ to $\left[\left(\frac{1-\alpha}{2}\right)\pi + \alpha\pi\right] = (1+\alpha)\frac{\pi}{2}$

$f(x) = 0$ from $\left(\frac{1+\alpha}{2}\pi\right)$ to $\pi + \left(\frac{1-\alpha}{2}\right)\pi$

$f(x) = F_{DM}\ \sin x$ from $\pi + \left(\frac{1-\alpha}{2}\right)\pi$ to $\pi + (1+\alpha)\frac{\pi}{2}$

$$A_1 = \frac{1}{\pi}\left[\int_{(1-\alpha)\pi/2}^{(1+\alpha)\pi/2} F_{DM}\ \sin^2 x\ dx + \int_{\pi+(1-\alpha)\pi/2}^{\pi+(1+\alpha)\pi/2} F_{DM}\ \sin^2 x\, dx\right]$$

$$\int \sin^2 x\ dx = \frac{1}{2}x - \frac{1}{4}\sin 2x$$

$$A_1 = \frac{F_{DM}}{\pi}\left[\left(\frac{1}{2}x - \frac{1}{4}\sin 2x\right)_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} + \left(\frac{1}{2}x - \frac{1}{4}\sin 2x\right)_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}}\right]$$

$$A_1 = \frac{F_{DM}}{\pi}\left[(1+\alpha)\frac{\pi}{4} - \frac{1}{4}\sin(\pi+\alpha\pi) - (1-\alpha)\frac{\pi}{4} + \frac{1}{4}\sin(\pi-\alpha\pi) + \frac{\pi}{2} + (1+\alpha)\frac{\pi}{4}\right.$$

$$\left. - \frac{1}{4}\sin(2\pi+\pi+\alpha\pi) - \frac{\pi}{2} - (1-\alpha)\frac{\pi}{4} + \frac{1}{4}\sin(2\pi+\pi-\alpha\pi)\right]$$

$$\sin(x+y) = \sin x \cos y + \cos x \sin y$$

$$\sin(\pi+\alpha\pi) = -\sin\alpha\pi$$

$$\sin(3\pi+\alpha\pi) = -\sin\alpha\pi$$

$$\sin(\pi-\alpha\pi) = +\sin\alpha\pi$$

$$\sin(3\pi-\alpha\pi) = +\sin\alpha\pi$$

$$A_1 = \frac{F_{DM}}{\pi}\left[\frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin\alpha\pi - \frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin\alpha\pi + \frac{\pi}{2} + \frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin\alpha\pi\right.$$
$$\left. - \frac{\pi}{2} - \frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin\alpha\pi\right]$$

$$A_1 = \frac{F_{DM}}{\pi}\left[\alpha\pi + \sin\alpha\pi\right]$$

The amplitude of the fundamental of the field MMF will be

$$A_{1f} = \frac{1}{\pi}\int_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} N_f I_f \sin x\,dx + \int_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}} N_f I_f \sin x\,dx$$

$$A_{1f} = \frac{N_f I_f}{\pi}\left[\left(-\cos x\right)_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} + \left(-\cos x\right)_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}}\right]$$

$$A_{1f} = \frac{N_f I_f}{\pi}\left[-\cos\left(\frac{\pi}{2}+\frac{\pi\alpha}{2}\right)+\cos\left(\frac{\pi}{2}-\frac{\pi\alpha}{2}\right)-\cos\left(\frac{3\pi}{2}+\frac{\pi\alpha}{2}\right)+\cos\left(\frac{3\pi}{2}-\frac{\pi\alpha}{2}\right)\right]$$

$$\cos(x+y) = \cos x \cos y - \sin x \sin y$$

$$\cos\left(\frac{\pi}{2}+\frac{\pi\alpha}{2}\right) = -\sin\frac{\pi\alpha}{2}$$

$$\cos\left(\frac{3\pi}{2}+\frac{\pi\alpha}{2}\right) = -\sin\frac{\pi\alpha}{2}$$

$$\cos\left(\frac{\pi}{2}-\frac{\pi\alpha}{2}\right) = \sin\frac{\pi\alpha}{2}$$

$$\cos\left(\frac{3\pi}{2}-\frac{\pi\alpha}{2}\right) = \sin\frac{\pi\alpha}{2}$$

$$A_{1f} = \frac{N_f I_f}{\pi}\left[\sin\frac{\pi\alpha}{2}+\sin\frac{\pi\alpha}{2}+\sin\frac{\pi\alpha}{2}+\sin\frac{\pi\alpha}{2}\right] = \frac{N_f I_f}{\pi}\left(4\sin\frac{\pi\alpha}{2}\right)$$

The demagnetizing factor in the direct axis is found by equating A_1 and A_{1f}

$$\frac{N_f I_f}{\pi}\left(4\sin\frac{\pi\alpha}{2}\right) = \frac{F_{DM}}{\pi}\left(\alpha\pi + \sin\alpha\pi\right)$$

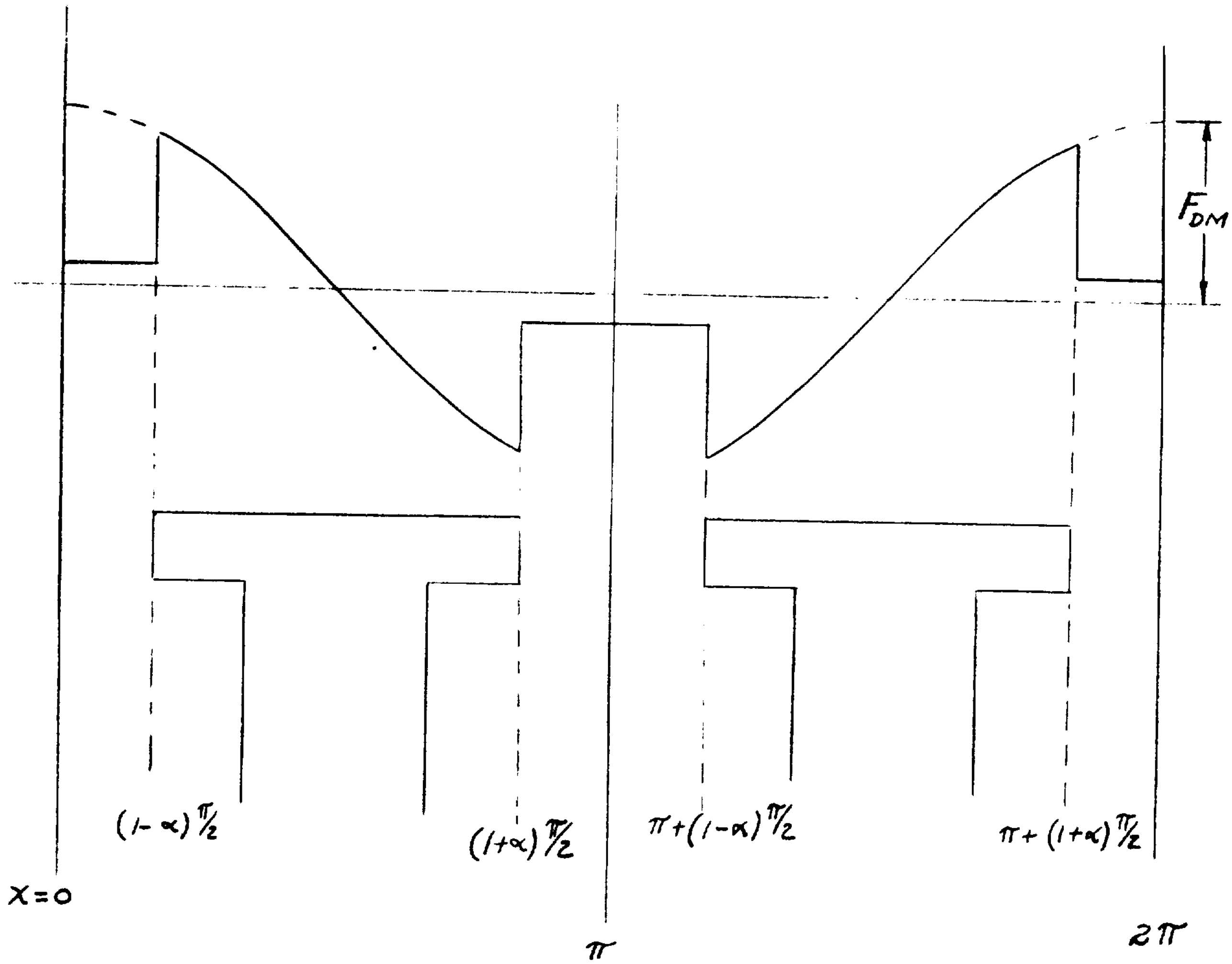
$$N_f I_f = \frac{F_{DM}}{\pi}\left(\alpha\pi + \sin\alpha\pi\right)\frac{\pi}{4\sin\frac{\pi\alpha}{2}} = C_M F_{DM}$$

$$\text{where} \quad C_M = \frac{\alpha\pi + \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$$

Although this derivation has been based on the assumption that the air gap under the pole is constant, the formula is much more accurate than might appear. The formula has been checked by flux plots over a wide range of pole shapes from 4 to 88 poles and found to be reasonable accurate

Cq

QUADRATURE AXIS COMPONENT OF ARMATURE REACTION



For all practical purposes the armature MMF in the quadrature axis will have the shape indicated insofar as its reaction on the field is concerned. If the assumption (justified by practice) is made that the magnitude of the constant part over the interpolar space is equal to 1/8 F_{DM}' , the fundamental of this wave will then be found by the equation

$$A_1 = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos x\,dx$$

$f(x) = \frac{1}{8}F_{DM}$ from $x = 0$ to $x = (1-\alpha)\pi/2$

$f(x) = F_{DM}\cos x$ from $(1-\alpha)\pi/2$ to $(1+\alpha)\pi/2$

$f(x) = -\frac{1}{8}F_{DM}$ from $(1+\alpha)\pi/2$ to $\pi+(1-\alpha)\pi/2$

$f(x) = F_{DM}\cos x$ from $\pi+(1-\alpha)\pi/2$ to $\pi+(1+\alpha)\pi/2$

$f(x) = \frac{1}{8}F_{DM}$ from $\pi+(1+\alpha)\pi/2$ to 2π

$$A_1 = \left[\begin{array}{l} \frac{1}{\pi}\int_0^{(1-\alpha)\frac{\pi}{2}} \frac{F_{DM}}{8} \cos x\, dx + \frac{1}{\pi}\int_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} F_{DM} \cos^2 x\, dx \\ -\frac{1}{\pi}\int_{(1+\alpha)\frac{\pi}{2}}^{\pi+(1-\alpha)\frac{\pi}{2}} \frac{F_{DM}}{8} \cos x\, dx + \frac{1}{\pi}\int_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}} F_{DM} \cos^2 x\, dx + \frac{1}{\pi}\int_{\pi+(1+\alpha)\frac{\pi}{2}}^{2\pi} \frac{F_{DM}}{8} \cos x\, dx \end{array} \right]$$

$$\int \cos x\, dx = \sin x$$

$$\int \cos^2 x\, dx = \tfrac{1}{2} x + \tfrac{1}{4} \sin 2x$$

$$A_1 = \frac{F_{DM}}{8\pi}\left[\left(\sin x\right)_0^{(1-\alpha)\pi/2} - \left(\sin x\right)_{(1+\alpha)\pi/2}^{\pi+(1-\alpha)\pi/2} + \left(\sin x\right)_{\pi+(1+\alpha)\pi/2}^{2\pi} \right]$$

$$+ \frac{F_{DM}}{\pi}\left[\left(\frac{1}{2}x + \frac{1}{4}\sin 2x\right)_{(1-\alpha)\pi/2}^{(1+\alpha)\pi/2} + \left(\frac{1}{2}x + \frac{1}{4}\sin 2x\right)_{\pi+(1-\alpha)\pi/2}^{\pi+(1+\alpha)\pi/2} \right]$$

$$A_1 = \frac{F_{DM}}{8\pi}\left[\sin\left(\frac{\pi}{2} - \frac{\pi\alpha}{2}\right) - \sin\left(\frac{3\pi}{2} - \frac{\pi\alpha}{2}\right) + \sin\left(\frac{\pi}{2} + \frac{\pi\alpha}{2}\right) - \sin\left(\frac{3\pi}{2} + \frac{\pi\alpha}{2}\right) \right]$$

$$+ \frac{F_{DM}}{\pi}\left[\frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin(\pi + \alpha\pi) - \frac{1}{4} + \frac{\alpha\pi}{4} - \frac{1}{4}\sin(\pi - \alpha\pi) + \frac{3\pi}{4} + \frac{\alpha\pi}{4} \right.$$

$$\left. + \frac{1}{4}\sin(3\pi + \alpha\pi) - \frac{3\pi}{4} + \frac{\alpha\pi}{4} - \frac{1}{4}\sin(3\pi - \alpha\pi) \right]$$

$$\sin(x+y) = \sin x \cos y + \cos x \sin y$$

$$\sin(x-y) = \sin x \cos y - \cos x \sin y$$

$$\sin\left(\frac{\pi}{2} - \frac{\pi\alpha}{2}\right) = \cos\frac{\pi\alpha}{2} \qquad \sin\left(\frac{3\pi}{2} - \frac{\pi\alpha}{2}\right) = -\cos\frac{\pi\alpha}{2}$$

$$\sin\left(\frac{\pi}{2} + \frac{\pi\alpha}{2}\right) = \cos\frac{\pi\alpha}{2} \qquad \sin\left(\frac{3\pi}{2} + \frac{\pi\alpha}{2}\right) = -\cos\frac{\pi\alpha}{2}$$

$$\sin(\pi + \alpha\pi) = -\sin\alpha\pi \qquad \sin(\pi - \alpha\pi) = \sin\alpha\pi$$

$$\sin(3\pi + \alpha\pi) = -\sin\alpha\pi \qquad \sin(3\pi - \alpha\pi) = \sin\alpha\pi$$

$$A_1 = \frac{F_{DM}}{8\pi}\left[\cos\frac{\pi\alpha}{2} + \cos\frac{\pi\alpha}{2} + \cos\frac{\pi\alpha}{2} + \cos\frac{\pi\alpha}{2} \right] + \frac{F_{DM}}{\pi}\left[\frac{\pi}{4} + \frac{\alpha\pi}{4} - \sin\frac{\alpha\pi}{4} \right.$$

$$\left. - \frac{\pi}{4} + \frac{\alpha\pi}{4} - \sin\frac{\alpha\pi}{4} + \frac{3\pi}{4} + \frac{\alpha\pi}{4} - \sin\frac{\alpha\pi}{4} - \frac{3\pi}{4} + \frac{\alpha\pi}{4} - \sin\frac{\alpha\pi}{4} \right]$$

$$A_1 = \frac{F_{DM}}{2\pi}\left(\cos\frac{\pi\alpha}{2}\right) + \frac{F_{DM}}{\pi}\left(\alpha\pi - \sin\alpha\pi\right) = \frac{F_{DM}}{\pi}\left(\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi\right)$$

The amplitude of the fundamental of the field MMF was derived in the determination of C_M and

$$A_{1f} = \frac{N_f I_f}{\pi}\, 4\sin\frac{\alpha\pi}{2}$$

The demagnetizing factor in the quadrature axis is found by equating A_1 and A_{1f}

$$\frac{N_f I_f}{\pi}\, 4\sin\frac{\pi\alpha}{2} = \frac{F_{DM}}{\pi}\left(\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi\right)$$

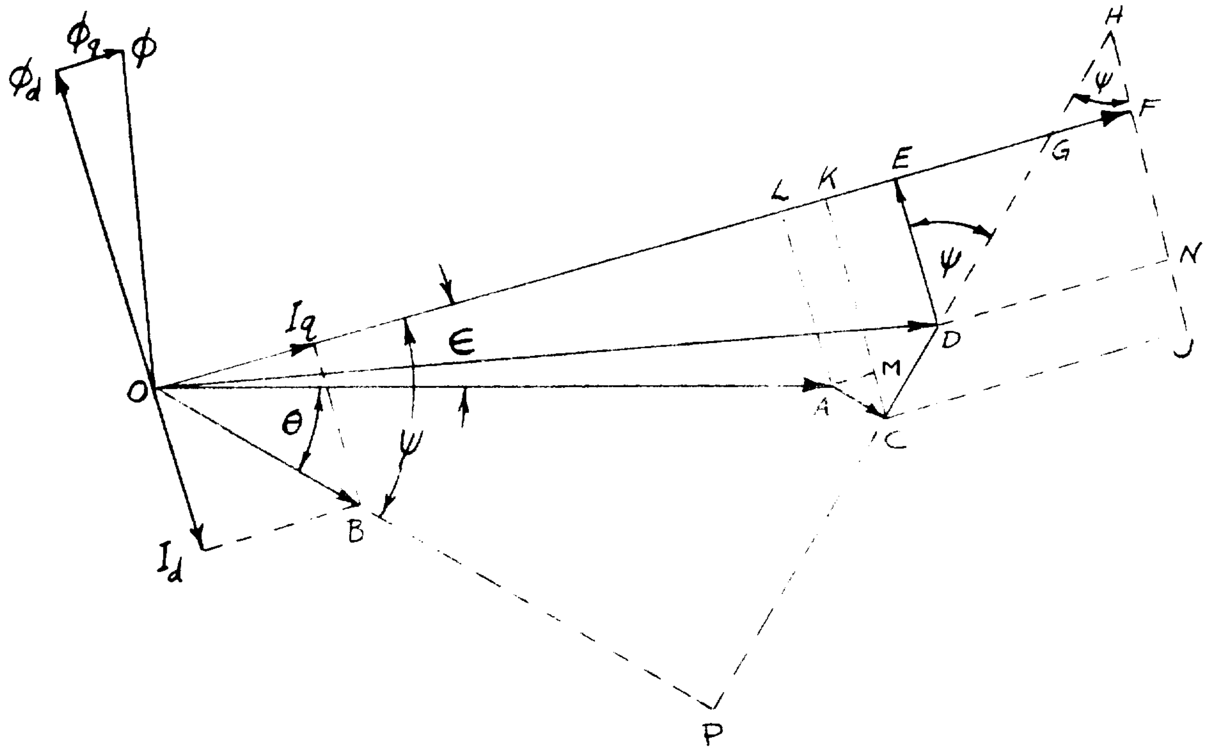
$$N_f I_f = F_{DM}\left[\frac{\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi}{4\sin\frac{\pi\alpha}{2}}\right] = F_{DM}\, C_q$$

where

$$C_q = \frac{\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi}{4\sin\frac{\pi\alpha}{2}}$$

VECTOR DIAGRAM AND CALCULATION OF LOAD

EXCITATION OF A SALIENT POLE GENERATOR



The vector diagram for a salient pole generator is as shown above. OA is the terminal voltage E_{ph} and OB is the phase current I_{ph} drawn at the proper power factor angle θ. AC is the effective resistance drop I_{ph} r_e and CD is the leakage reactance drop I_{ph} X_ℓ. The stator current is divided into a direct axis component I_d and a quadrature axis component I_q, and I_d X_{ad} will thus be the voltage induced in the stator by the direct axis flux ϕ_d and I_q X_{aq} will be the voltage induced in the stator by the cross flux ϕ_q. The voltage I_q X_{aq} will be in quadrature with ϕ_q and it is represented by DE. Likewise, the voltage I_d X_{ad} will be in quadrature with ϕ_d and it is represented by EF. The voltage OF is the voltage that would exist at no load with excitation corresponding to rated load, neglecting saturation, and this voltage is represented by the symbol e_d.

Consider the triangle OI_q B and

$$\sin\psi = \frac{I_d}{OB} = \frac{I_d}{I_{ph}}; \quad I_d = I_{ph}\sin\psi$$

$$\cos\psi = \frac{I_q}{OB} = \frac{I_q}{I_{ph}}; \quad I_q = I_{ph}\cos\psi$$

The triangles OI_q B and DEG are similar because EG is perpendicular to I_q B, GD is perpendicular to BO, and DE is perpendicular to OI_q. Thus angle O is equal to angle D. Also, triangles DEG and HFG are similar because DE is parallel to HF, EG is concentric with FG, and GD is concentric with GH, and therefore angle D and angle H are equal. From a similar triangle relationship the angle A of triangle AMC is also equal to ψ.

From triangle DHN

$$\sin\psi = \frac{DN}{DH} = \frac{I_d X_{ad}}{DH}$$

$$DH = \frac{I_d X_{ad}}{\sin\psi} = \frac{I_d X_{ad}}{I_d/I_{ph}} = I_{ph} X_{ad}$$

$$CH = I_{ph} X_{ad} + I_{ph} X_\ell = I_{ph} X_d$$

$$CJ = KF = CH \sin\psi = I_{ph} X_d \sin\psi$$

$$OL = OA\cos\epsilon = E_{ph}\cos\epsilon$$

$$AM = LK = I_{ph} r_e \cos\psi$$

Thus the nominal voltage e_d is derived as

$$e_d = OL + LK + KF$$

$$e_d = E_{ph}\cos\epsilon + I_{ph}(r_e\cos\psi + X_d \sin\psi)$$

In the per unit system of notation E_{ph} and I_{ph} are unity at rated load conditions and if resistance is neglected the nominal voltage equation becomes

$$e_d = \cos\epsilon + X_d \sin\psi$$

From triangle DEG

$$\cos \psi = \frac{DE}{DG} = \frac{I_q X_{aq}}{DG}$$

$$DG = \frac{I_q X_{aq}}{\cos \psi} = \frac{I_q X_{aq}}{I_q / I_{ph}} = I_{ph} X_{aq}$$

$$CG = CD + DG = I_{ph} X_\ell + I_{ph} X_{aq} = I_{ph} X_q$$

Therefore, if resistance is again neglected the angles $\in$ and ψ can be determined by

$$Tan\ \psi = \frac{PG}{OP} = \frac{I_{ph} X_q + E_{ph} \sin \theta}{E_{ph} \cos \theta} = \frac{X_q + \sin \theta}{\cos \theta}$$

When load is applied to the generator the flux wave shape will be distorted and the wave form under load will be less effective in generating voltage than the no load wave form. The reason for this is that the fundamental of the wave form under load is relatively less than that of the no load form for an equal total flux per pole under each condition. Therefore the flux per pole under load conditions will be greater than that required at no load, and the flux per pole under load is

$$\phi_{PL} = \phi_P \left[e_d - .93\, X_{ad} \sin \psi \right]$$

The leakage flux under load will also increase and

$$\phi_{\ell\ell} = \phi_\ell \left[\frac{e_d F_g + (1 + \cos \theta) F_T + F_c}{F_g + F_T + F_c} \right]$$

The total flux per pole in the rotor thus becomes

$$\phi_{pt\ell} = \phi_{PL} + \phi_{\ell\ell}$$

and the density of the pole under load is

$$B_{PL} = \frac{\phi_{pt\ell}}{a_p}$$

The total ampere turns per pole under load can thus be calculated as

$$F_L = e_d F_g + (1 + \cos \theta) F_T + F_c + F_{PL}$$

SINGLE PHASE CALCULATIONS

When two phases of a normal three phase generator are used for single phase operation the machine reactances are first calculated on the basis of a three phase machine and the single phase reactances then become:

$$X_{ad}(1\phi) = \frac{X_{ad}(3\phi)}{\sqrt{3}}$$

$$X_d(1\phi) = \frac{X_d(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

$$X_q(1\phi) = \frac{X_q(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

$$X_d'(1\phi) = \frac{X_d'(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

$$X_d''(1\phi) = \frac{X_d''(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

The negative sequence component of the single phase armature reaction wave will induce large currents in the damper winding and this will cause high damper losses under load conditions. Until further experience is accumulated it is not felt advisable to exceed current densities of 10,000 amps/sq. in. in the damper bars under normal load conditions when the current is calculated in the following manner.

$$\text{NEG. SEQ. A.T.} = \frac{[X_{ad}(3\,\text{phase})]\,F_g}{\sqrt{3}}$$

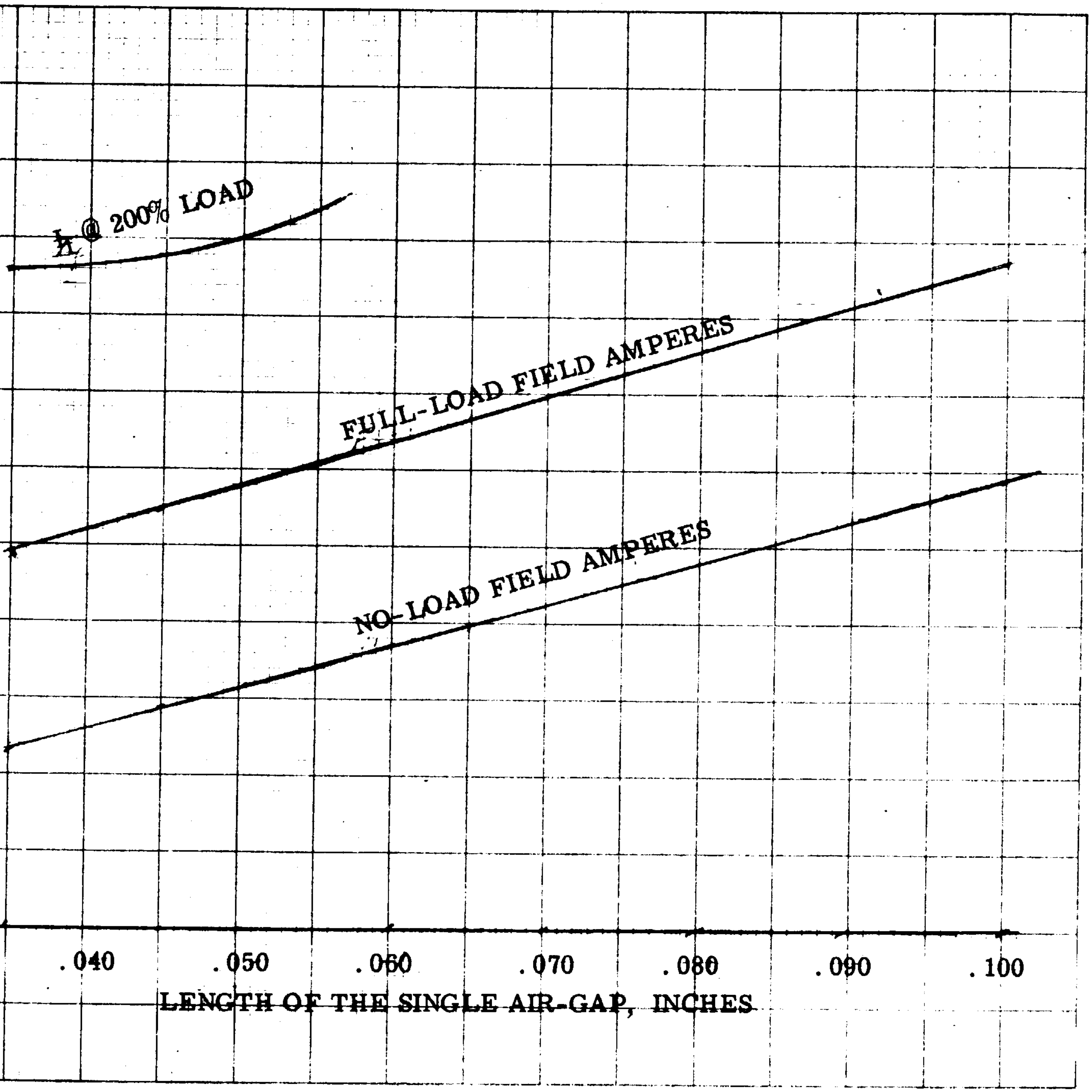
$$I_{\text{RMS PER BAR}} = \frac{(\pi)(\text{NEG. SEQ. A.T.})}{(\sqrt{2})(n_b + 1)}$$

EFFECT OF INCREASING THE AIR GAP

THE EFFECT OF INCREASING THE AIR-GAP

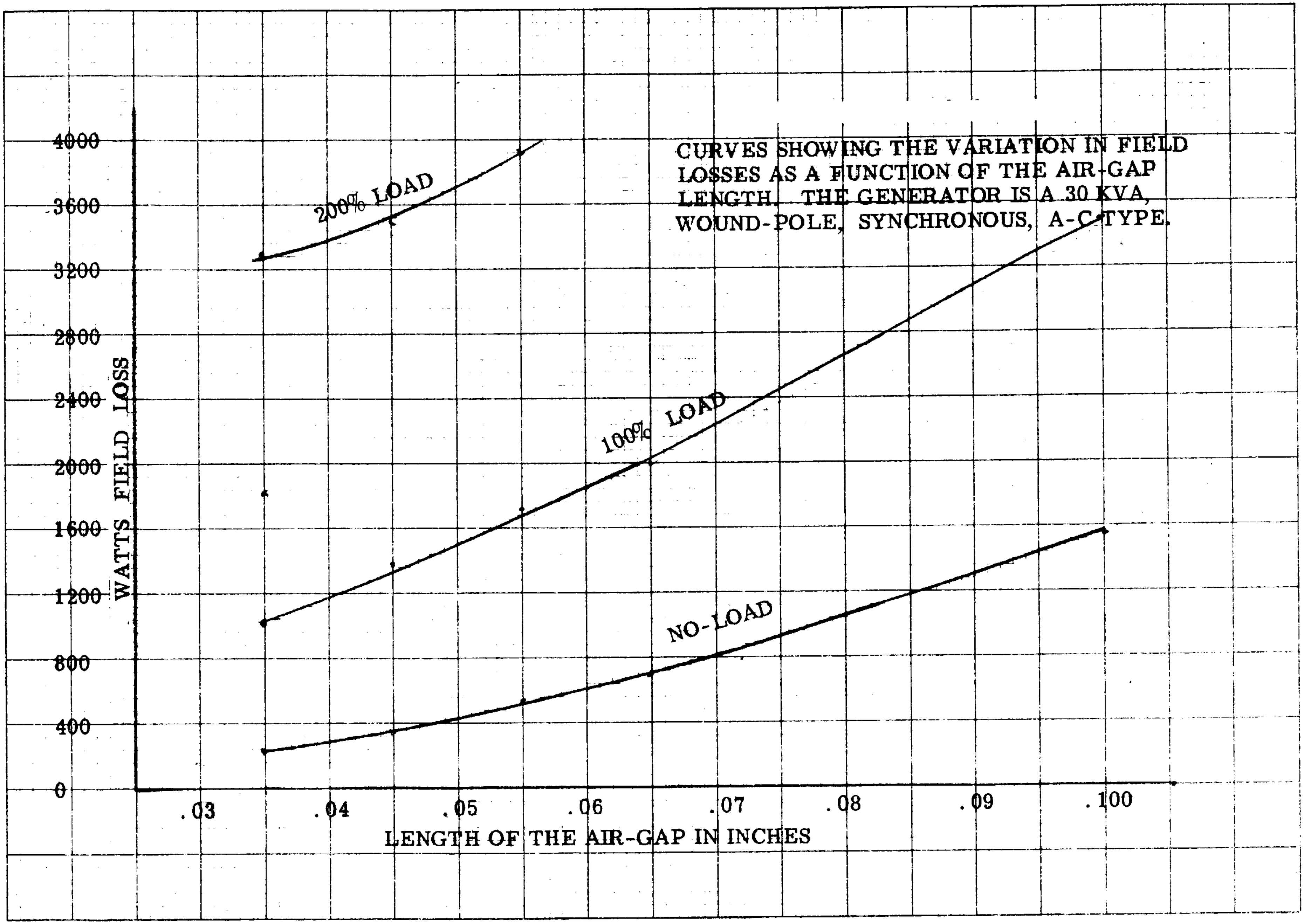
The losses and reactances of a 30 KVA, 320 CPS, 4800 rpm aircraft generator were calculated for various air-gap lengths. The stator and its output winding were both held unchanged for the range of air-gap lengths.

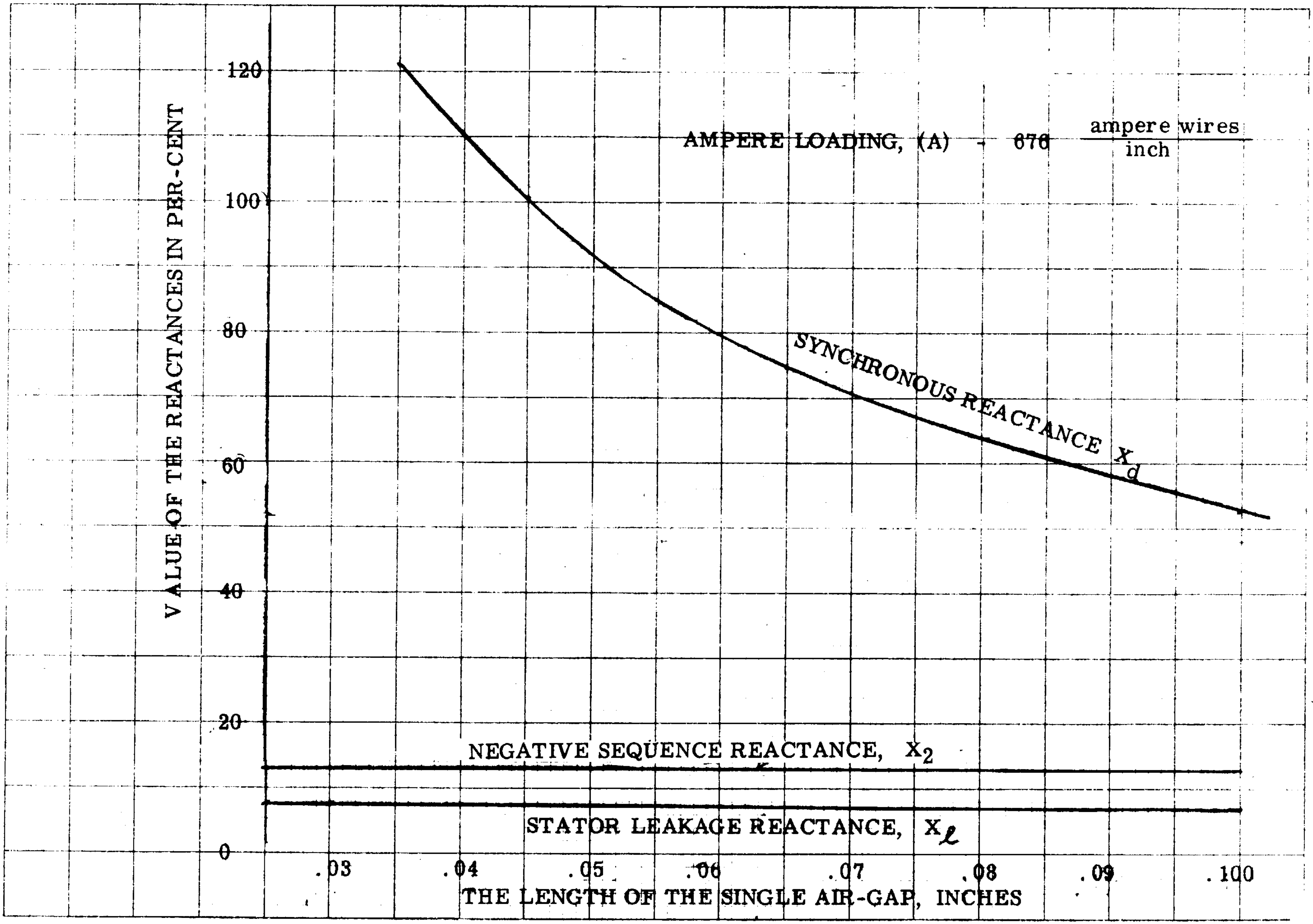
As would be expected under these conditions, the field excitation requirement soon limits the output and, for this particular machine, the thermal limit for continuous full load operation would be reached when the air-gap was increased from .035" to .055", an increase of 57%.



...d-Pole A-C
...hanged

...ield Current		
...oad	$I_{1\text{-}1/2\,L}$ 150% Load	$I_{2\,L}$ 200% Load
	32	43
		44
		47


CURVES SHOWING THE VARIATION IN FIELD LOSSES AS A FUNCTION OF THE AIR-GAP LENGTH. THE GENERATOR IS A 30 KVA, WOUND-POLE, SYNCHRONOUS, A-C TYPE.
200% LOAD
100% LOAD
NO-LOAD
WATTS FIELD LOSS
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
.03
.04
.05
.06
.07
.08
.09
.100
LENGTH OF THE AIR-GAP IN INCHES


AMPERE LOADING, (A) - 676 $\frac{\text{ampere wires}}{\text{inch}}$
SYNCHRONOUS REACTANCE X_d
NEGATIVE SEQUENCE REACTANCE, X_2
STATOR LEAKAGE REACTANCE, X_ℓ
VALUE OF THE REACTANCES IN PER-CENT
120
100
80
60
40
20
0
.03
.04
.05
.06
.07
.08
.09
.100
THE LENGTH OF THE SINGLE AIR-GAP, INCHES

SALIENT POLE SYNCHRONOUS DESIGN SHEET

STATOR

Punching I.D.	7.25
Punching O.D.	9.25
Core Length	3.0
DBS x 2	1.132
Slots	96
Size Slots	.122 x .434
Carter Coeff.	1.082
Type Wdg.	ser. Y
Throw	83.3% 1 - 11
Skew & Dist. Fact.	.995 .958
Chord Fact.	.966
Cond. Per Slot	2
Total Eff. Cond.	184.8
Cond. Size	.075 x .162 SGHF
Cond. Area	.01194
Current Density	6970
Wdg. Const.	.397 C1 1.018
Total Flux	3550
Gap Area	68.4
Gap Density	52.0
Pole Const.	.650
Flux Per Pole	288
Tooth Pitch	.238
Tooth Density	107
Core Density	92
Grade Of Iron	M 22 29 ga.
1/2 Mean Turn	6.99
Res. Per Ph. At 300°F	.0391
Eddy Fact. Top	1.185
Eddy Fact. Bottom	1.026
Demag. Fact. Cm	.84 Cq .52
Amp. Cond. Per In.	676
React. Factor	.867
Cond. Perm.	3.56
End Perm.	5.45
Leakage React.	7.8
Air Gap Perm.	152.5
React. Of Arm. Xad	113 Xaq 68.7
Wt. Of Copper	
Wt. Of Iron	

ROTOR

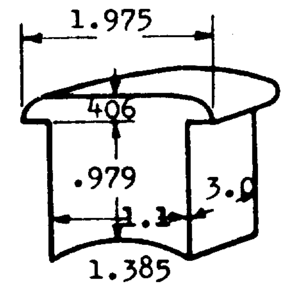
Single Gap	.035 ge .0379
Rotor Diameter	7.18
Peripheral Speed	
Pole Pitch	2.84 α .71
Pole Area	3.17
Side Leakage	.809
End Leakage	.419
Tip Leakage	.655
Leakage Flux	26
Pole Density	99.1
Grade Of Iron	M 36 22 ga.
No. Damper Bars	5
Bar Size	.156 dia.
Bar Pitch	.403 h_o .038 b_o .040
Turns Per Pole	68
Cond. Size	#14 .071 dia.
Cond. Area	SGSF .00322
Mean Turn	10.13
Res. At 300f o	1.79
Wt. Of Copper	
Wt. Of Iron	

% Load	0	100	
Amps.	11.6	24.6	
Volts 300°F	20.8	44.0	
Amps/In.^{2}	3600	7650	

Field Leak. React.	14.1
Field Self Induct.	.184
Damp. Leak. XDd	4.30 XDq 5.35

REACT.-TIME CONST.

Synch. Xd	121.0 Xq 76.7
Unsat. Trans.	22.1
Sat. Trans.	19.5
Subtrans. X''d	12.30 X''q 13.35
Neg. Sequence	12.8
Zero Sequence	3.5
Open Circ. Time Con. 300° F	.103
Arm. Time Con.	.00234
Trans. Time Con.	.0166
Subtrans. Time Con.	.0065



SATURATION

Air Gap A.T.	618
Stator A.T.	104
Pole A.T.	67
No Load A.T.	789
Rated Load A.T.	1675
Overload A.T.	-
Short Circ. A.T.	748
Short Circ. Ratio	1.055

LOSSES-EFFICIENCY

% Load	0	100	
F & W	137	137	
Sta. Teeth	131	166	
Sta. Core	310	310	
Pole Face	109	131	
Damper	4	5	
Sta. I^2R	-	815	(300°F)
Eddy		87	(300° F)
Rot. I^2R	239	1082	
Σ Losses		2732	
Rating		22500	
Rtg.+Loss		25232	
% Loss		10.8	
% Eff.		89.2	

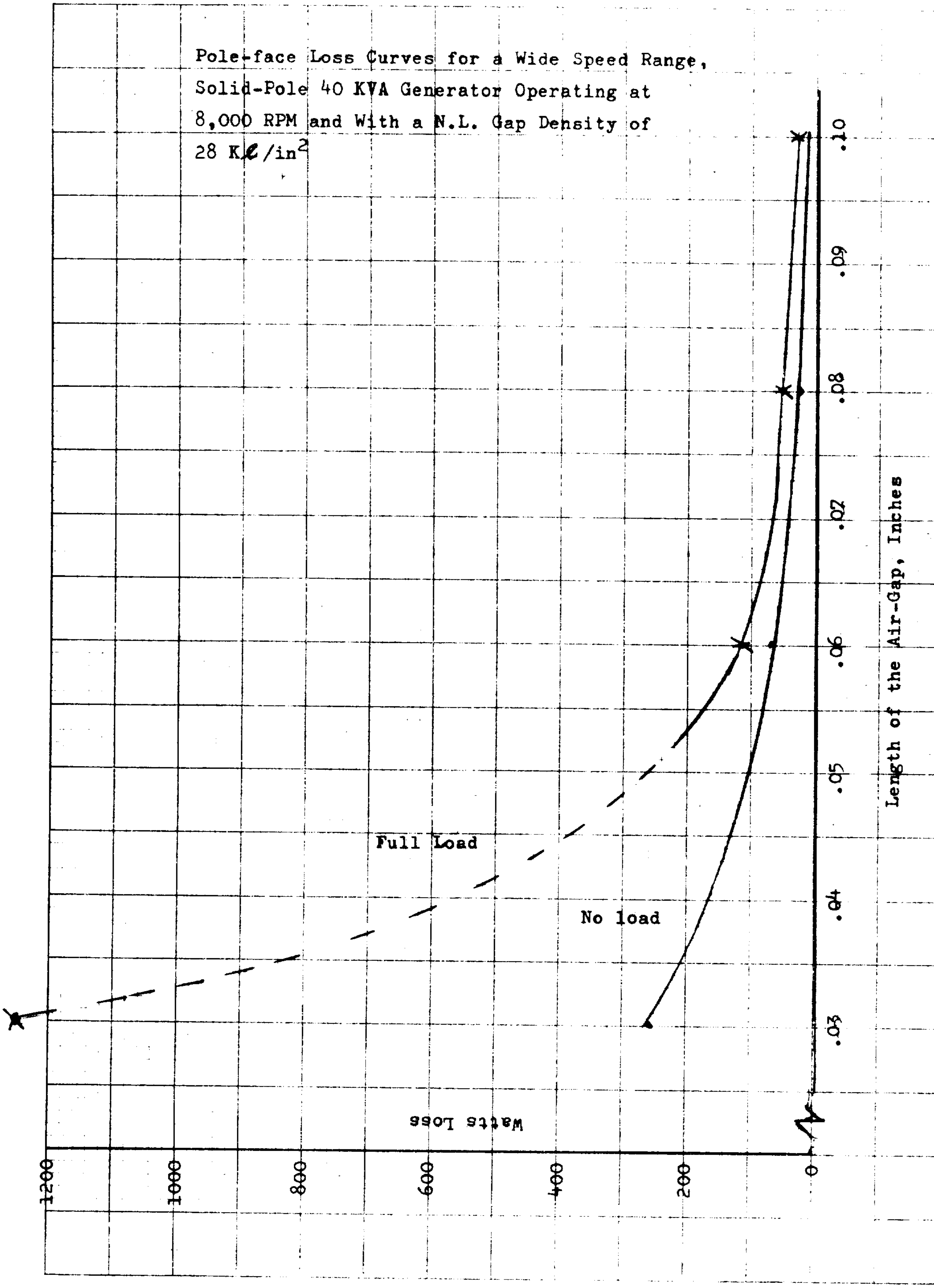
Stator Watts/In.^{2}	15.8
Rotor Watts/In.^{2}	18.0

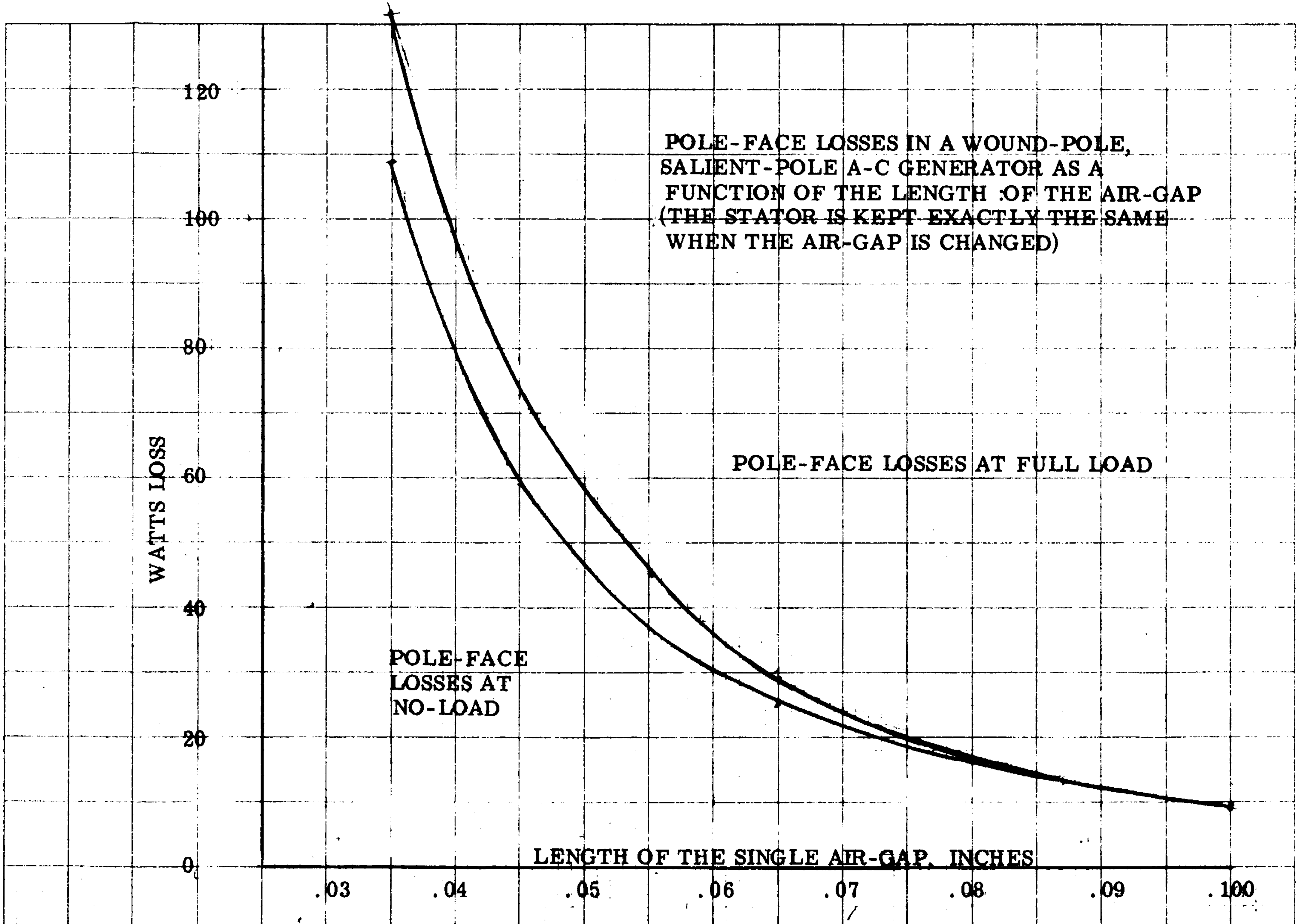
Type Cooling Air

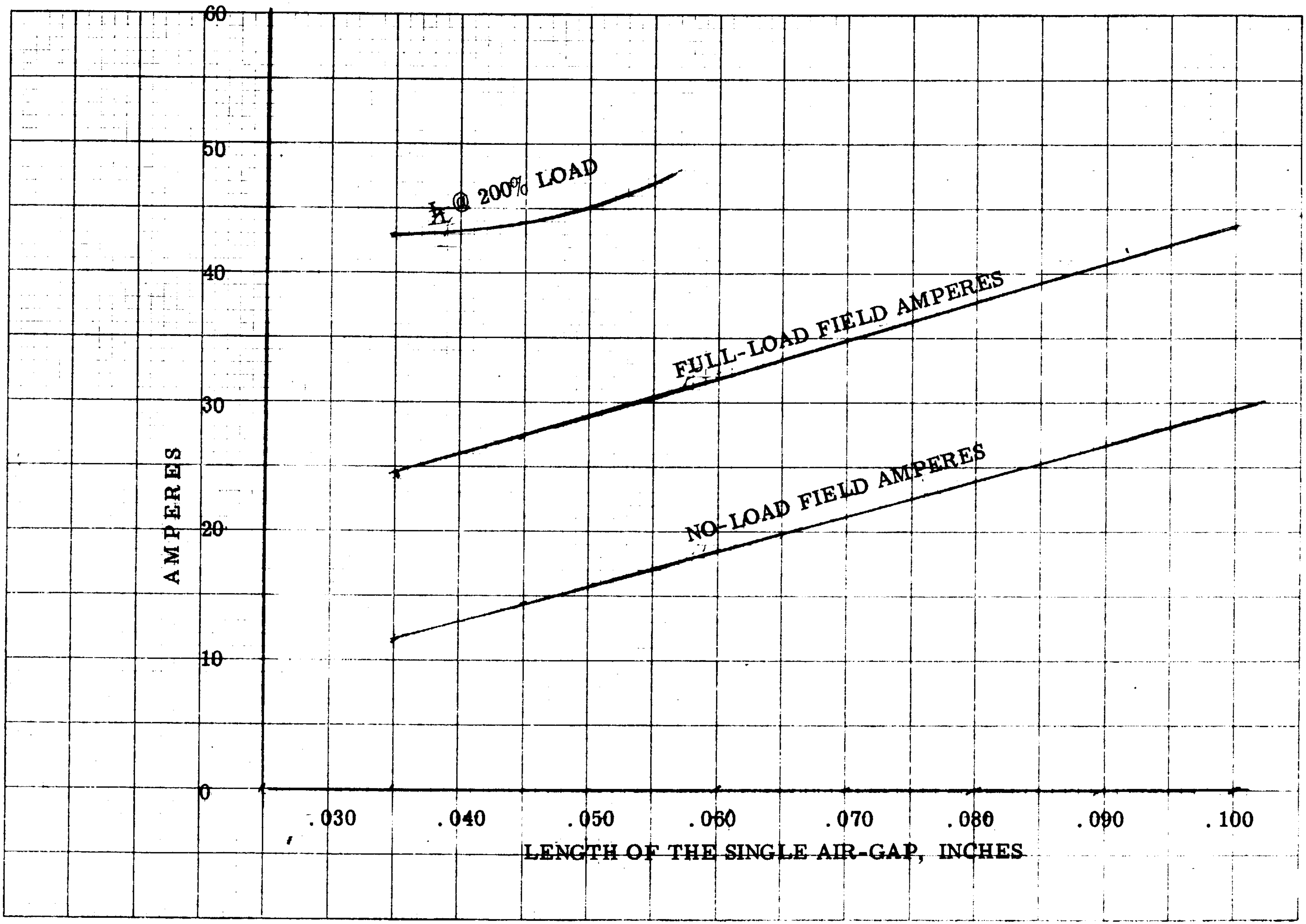
30 KVA 75 % PF 208 Volts 83.4 Amps. 3 Ph. 320 Cycles 4800 RPM

TA-7

Pole-face Loss Curves for a Wide Speed Range, Solid-Pole 40 KVA Generator Operating at 8,000 RPM and With a N.L. Gap Density of 28 Kℓ/in^2




POLE-FACE LOSSES IN A WOUND-POLE, SALIENT-POLE A-C GENERATOR AS A FUNCTION OF THE LENGTH OF THE AIR-GAP (THE STATOR IS KEPT EXACTLY THE SAME WHEN THE AIR-GAP IS CHANGED)
POLE-FACE LOSSES AT FULL LOAD
POLE-FACE LOSSES AT NO-LOAD
WATTS LOSS
120
100
80
60
40
20
0
LENGTH OF THE SINGLE AIR-GAP, INCHES
.03
.04
.05
.06
.07
.08
.09
.100



I_f @ 200% LOAD
FULL-LOAD FIELD AMPERES
NO-LOAD FIELD AMPERES
AMPERES
60
50
40
30
20
10
0
.030
.040
.050
.060
.070
.080
.090
.100
LENGTH OF THE SINGLE AIR-GAP, INCHES

Pole-Face Loss Curves for a Solid-Pole 40 KVA Generator Operating At 4400 RPM and With a N. L. Gap Density of 50 Kℓ/in^2